SIMULATION AND ANIMATION OF HETEROGENEOUS TRAFFIC ON URBAN ROADS

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for the Degree of

Ph.D.

by

BHUVANESH SINGH

to the

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INDIAN INSTITUTE OF TECHNOLOGY KANPUR

June, 1999

CERTIFICATE

It is certified that the work contained in the thesis entitled *"Simulation and Animation of Heterogeneous Traffic on Urban Roads"*, by **Mr. Bhuvanesh Singh**, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

June /c, 1999

Dr. B. R. Marwah
Professor
Department of Civil Engg. I.I.T.
Kanpur

To
My Father and Mother,
With
Profound Respect

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Bhuvanesh Singh

Contents

List of Figures

List of Tables

LIST OF SYMBOLS AND ABBREVIATIONS

ADV	Animal Driven Vehicle
BDS	Basic Desired Speed
CAG	Computer Aided Graphics
CBD	Central Business District
CRRI	Central Road Research Institute
C_a	Coefficient of Air Resistance
C_{r1}, C_{r2}	Rolling Resistance Coefficients
D	Density
Dec	Maximum Deceleration Rate
DV-unit	Driver Vehicle Unit
D_j	Jam Density
D_m	Concentration at Maximum Flow
EDVU	Equivalent Design Vehicle Unit
FHWA	Federal Highway Administration
FSD	Flow Status Diagram
F_L	Air Resistance in Newtons
F_r	Rolling Resistance in Newtons
GDS	Graphic Display System
GKS	Graphics Kernel System
GPGS	General Purpose Graphics System
GRITS	Graphical Interactive Traffic Simulation
HCM	Highway Capacity Manual
HCV	Heavy Commercial Vehicle
HDM	Highway Design Model
HMV	Heavy Motorised Vehicle
I	Image Size
ICG	Interactive Computer Graphics
IITK	Indian Institute of Technology Kanpur
INTRAS	Integrated Traffic Simulation
ITSIM	Indian Traffic Simulation Model
IVLS	Inter-Vehicular Lateral Spacing
LCV	Light Commercial Vehicle
LOS	Level of Service
MIXNETSIM	Mixed Traffic Network Simulation Model
MIXSIM	Mixed Traffic Simulation Model
MOE	Measure of Effectiveness
MORTAB	Model for Road Traffic Behaviour
MTW	Motorised Two Wheeler

MV	Motorised Vehicle
NCU	National Commission on Urbanisation
NMV	Non-Motorised Vehicle
NOVRT	Number of Overtakings
PCU	Passenger Car Unit
PCE	Passenger Car Equivalent
PHF	Peak Hour Factor
PWR	Power/weight ratio
RUCS	Road User Cost Study
SDC	Systems Development Corporation
SWERTS	Swedish Road Traffic Simulation Model
T	Reaction Time of Following Vehicle Driver
TRASMIC	Traffic Simulation of Mixed Condition
TSD	Time Space Diagram
T_1	Average Headway of Free Flowing Vehicles in Seconds
T_2	Average Headway of Constrained Vehicles in Seconds
T_{n1}	Average Headway of Free Flowing NMV's in Seconds
T_{m1}	Average Headway of Free flowing MV's in Seconds
T_{n2}	Average Headway of Constrained NMV's in Seconds
T_{m2}	Average Headway of Constrained MV's in Seconds
UTSM	Urban Traffic Simulation Model
U_f	Mean Free Speed
U_m	Speed at Maximum Flow
U_s	Average Space Mean Speed
V	Total Number of Vehicles Arriving During Time T
VTI	Vag-Och Traffic Institute
Vd	Value of One Scalar Division
V_{ec}	Maximum Expected Speed in the Next Time Interval
V_{fr}	Speed of Front Vehicle
V_{re}	Speed of Rear Vehicle
cu_sp	Current Speed
g	Acceleration due to gravity
h	Time Headway in seconds
hl_{ovt}	Head Length of Overtaking Vehicle
i	Gradient
kmph	Kilometre per hour
ls_fo	Lateral Spacing Required from Physical Barriers
l_d	Interaction Distance, which is Separation Between Overtaking and Overtaken Vehicles

m	Vehicle mass in *kg*
max_ls	Maximum Lateral Space
min_ls	Minimum Lateral Space
min_sp	Minimum Speed of a Vehicle Group
max_sp	Maximum Speed of a Vehicle Group
m_t	Minimum Tail Length
ovt_{sp}	Overtaking Speed
ovn_{sp}	Overtaken Speed
p	Power/Mass Ratio
$prob_{ov}$	Probability of Overtaking
$prob_y$	Probability of Yielding
$p(h < t)$	Probability of Headway Less than t
sl_{fa}	Search Length for the Frontal Search Area
sl_{lfa}	Search Length for the Left Frontal Search Area
sl_{lra}	Search Length for the Left Rear Search Area
sl_{ra}	Search Length for the Rear Search Area
sw_{fa}	Search Width for the Front Search Area
sw_{lfa}	Search Width for the Left Frontal Search Area
sw_{lra}	Search Width for the Left Rear Search Area
sw_{ra}	Search Width for the Rear Search Area
t_h	Minimum Time Headway
tl_{ovn}	Tail Length of Overtaken Vehicle
v	Vehicle Speed in m/sec
vph	Vehicles Per Hour
v_{fr}	Free Speed
v_{ent}	Entrance Speed
$x_n(t)$	Position of Lead Vehicle (n) at Time t
$x_{n+1}(t)$	Position of Lead Vehicle (n+1) at Time t
$\ddot{x}_{n+1}(t+T)$	Acceleration of Following Vehicle (n+1) at Time (t+T)
$\dot{x}_n(t)$	Velocity of Lead Vehicle (n) at Time t
$\dot{x}_{n+1}(t)$	Velocity of Following Vehicle (n+1) at Time t
α_0	Sensitivity Constant having Unit of Velocity
α_{cn}	Fraction of Total Flow Made up of Constrained NMV's
α_{cm}	Fraction of Total Flow Made up of Constrained MV's
α_{un}	Fraction of Total Flow Made up of Unconstrained NMV's
α_{um}	Fraction of Total Flow Made up of Unconstrained MV's
Δ t	Time Increment for Simulation time
Δ x	Width of Grid Element
Δ y	Length of Grid Element

ΔFS	Difference in Free Speed of Overtaking and Overtaken Vehicles
$\Delta FS_{MIN_{OV}}$	Minimum Difference in Free Speed of Overtaking and Overtaken Vehicles Below which Probability of Overtaking is Zero
$\Delta FS_{MAX_{OV}}$	Maximum Difference in Free Speed of Overtaking and Overtaken Vehicles Above which Probability of Overtaking is One
$\Delta IVLS_{MIN_{OV}}$	Minimum Inter-Vehicular Lateral Spacing Below which Probability of Overtaking is Zero
$\Delta IVLS_{MAX_{OV}}$	Maximum Inter-Vehicular Lateral Spacing Above which Probability of Overtaking is One
ΔFS_{MIN_Y}	Minimum Difference in Free Speed of Overtaking and Overtaken Vehicles Below which Probability of Yielding is Zero
ΔFS_{MAX_Y}	Maximum Difference in Free Speed of Overtaking and Overtaken Vehicles Above which Probability of Yielding is One
$\Delta IVLS_{MIN_Y}$	Minimum Inter-Vehicular Lateral Spacing Below which Probability of Yielding is One
$\Delta IVLS_{MAX_Y}$	Maximum Inter-Vehicular Lateral Spacing Above which Probability of Yielding is Zero
τ_n	Shift of Curve (i.e. minimum headway) for Constrained NMV's in seconds
τ_m	Shift of Curve (i.e. minimum headway) for Constrained MV's in seconds
τ	Shift of Curve (i.e. minimum headway) for Constrained Vehicles in seconds

SYNOPSIS

The flow of heterogeneous traffic on urban roads is highly complex and the existing analytical models cannot be used to predict the flow behaviour. Very limited research has been attempted for simulating heterogeneous traffic on urban corridors. The available models with reference to simulation of urban heterogeneous traffic have limitations with reference to lane discipline, overtaking/yielding behaviour (meandering of narrow motorised and non-motorised vehicles), calibration and validation of models based on the observed flow process etc. Considering the limitations of existing simulation models and need of developing new tool to justify the alternative urban traffic operational policies and measures, a model has been developed to simulate and animate the flow of urban heterogeneous traffic.

Traffic simulation system consists of various component submodels which are assembled into a realistic structure of the system. The heart of the system is the development of traffic simulation model, which simulates the flow of vehicles. Road and traffic submodels are developed to generate the road and traffic input respectively for the simulation model. To get the feel about working of the simulation model, animation program system is developed to have the graphic display of the simulated traffic. The model output is analysed through traffic results processing program to get the statistics of different performance measures. Some parameters of traffic flow are estimated through analysis of the field traffic data. Calibration of model parameters and decision thresholds is attempted by estimated traffic flow parameters and also through simulation experiments. The simulation model is validated for a number of measures of effectiveness (MOE). The validated simulation model is used to conduct a series of simulation runs to judge the sensitivity of some road and traffic characteristics. For its simplicity and portability, C language is used to program the model system. The Starbase Graphics Library is used for animating traffic and displaying various traffic flow parameters.

Study indicates that about 20 vehicle types use the same roadway. Therefore, different types of vehicles are aggregated into eight groups depending upon close resemblance in terms of physical and operational characteristics.

To realistically represent the road system for mixed traffic, the road is represented by a grid pattern. Vehicle is defined as an object, consisting of static and dynamic variables. Static variables are input to the simulation model and are generated from stochastic distributions. Dynamic variables change with time and their values depend upon logical decisions taken by the vehicle. Two different models have been proposed for traffic generation. The first model directly uses field data for traffic generation while the second model attempts to generate generalised traffic in which the attributes are randomised.

Broad categories of flow status for vehicles are free flowing; constrained flowing; and overtaking and yielding. For convenience in micro-level analysis, various movement types in each flow status are termed as 'mode'. Relationships are established with regard to longitudinal spacing (head length, tail length), inter-vehicular lateral spacing, lateral spacing from fixed objects, and search area. The flow logics in this model are classified as free, constrained, overtaking/passing, and yielding flow processes. In free flow situation, the vehicle moves at a uniform free speed of the road block. In the constrained flow situations, car following model is used to calculate acceleration rate based on relationship with the leading vehicle. The space headway polynomials derived from the field data are also used to compute minimum space headway between two interacting vehicles.

The overtaking behaviour of a vehicle is dependent on the difference between free speeds (ΔFS) of overtaking and overtaken vehicles, and available inter-vehicular lateral spacing ($IVLS$) between the two interacting vehicles at the time of decision making. The overtaking behaviour is represented by probability function. Two probability functions are constructed, one based on ΔFS and other based on inter-vehicular lateral spacing (IVLS). The probability of overtaking is the minimum of these two probabilities.

Decision making involved in passing process is identical to that of overtaking process. Maximum threshold spacing for yielding decision is same as in overtaking process. The yielding behaviour of front vehicle is stochastic in nature and is also dependent on the difference between free speed of front and rear vehicles and inter-vehicular lateral spacing between the two vehicles. Two probability functions are formulated and actual yielding probability is determined from them.

Graphical model is written in C programming language by using Starbase Graphics subroutines. Graphical model animates the traffic flow. Developed system of graphical models help in understanding the working of the simulation model logics and to validate the programme system of the component sub-models.

The field data was collected on major arterial of the Kanpur city. On various sections of this road, traffic volume is of the order of 1600-3000 vph during peak periods. Two sections

on the road are identified for data recordings. Free speed of motorised vehicles are recorded by Radar speedometer located at three different locations. Recording was done for 16 hours on two days. Video recording of traffic flow was done for a seven hour duration, which covered both peak and off peak periods with flow varying between 1600-3000 vph in each direction. In all data for about 25000 vehicles were recorded.

For traffic flow studies, the relevant information is extracted from the video recordings. Information for a vehicle relates to its longitudinal and lateral positions at a particular time. Spot speed of a vehicle can be obtained from the longitudinal positions of the vehicle at two closely spaced time intervals. It was planned to record the image size of the vehicle at appropriate times and then estimate the position of the vehicle. Due to problems in recording and extraction, the recorded vehicle image size may not be very accurate. So a detailed calibration of distance-image size relationships for different vehicle types is attempted.

Time headway analysis is done for six data sets, each of one hour duration. For the observed time headways, three composite headway distributions considered are: Schuhl, Modified-Schuhl (time headways of motorised and non-motorised vehicles are segregated), and Dawson composite headway distribution. Goodness of fit tested by K-S test confirm that Schuhl and Modified-Schuhl distributions describe the observed time headways. For the observed free speed data, Normal distributions were fitted for different vehicles type. Analysis was carried out for studying inter-vehicular lateral spacing, lateral spacing from physical barriers, longituidinal spacing, and overtaking and yielding behaviour.

The formulated traffic simulation model consists of a series of sub-models. The realistic estimate of various parameters and decision thresholds is attempted in the calibration process in three sequential stages.

The experimental simulation runs are made on the road for which the field observations are available. A stretch of 100 metre length is selected and traffic is simulated for two different flow levels. Comparison of the observed and simulated values of journey speeds for different vehicle types are made.

The model is validated for various measures of effectiveness such as journey speeds, time headways, traffic density, and number of overtakings performed. Simulation runs are made at flow level different from one used for calibration. This helps to test the capability of model under different conditions. Simulation run is made for an hourly volume of 2332 vph observed during the peak period. Comparison of simulated and observed output indicates the capability of the simulation model to realistically represent the complex heterogeneous traffic flow.

Sensitivity analysis of various road and traffic characteristics has been done by con-

ducting series of simulation runs. Initially a two lane (7m) wide level tangent road section (Road - I- benchmark road) is selected for simulation runs. To test the sensitivity of road width, two other roads of 10 m width (Road II) and 14 m width (Road III), are considered for simulation runs. The benchmark road and other two roads have unrestricted use by all non-motorised vehicles. To study the effect of restricting the road usage (segregation) of non-motorised vehicles, simulation experiments are also planned on 7 metre wide road where the non-motorised vehicle are restricted only to one lane (3.5 m width) adjacent to the road kerb.

Based on the observed traffic composition in Kanpur, a benchmark traffic composition level I (65 percent non-motorised vehicles and 35 percent motorised vehicles) is selected for simulation runs for all the three identified roads. To study the effect of traffic compositions, two more compositions (level II and III) are specified. Level II composition has equal share of motorised and non-motorised vehicles while level III composition has domination of motorised vehicles (motorised vehicles 65 percent, and non-motorised vehicles are 35 percent).

Road stretch of 500 metre length with additional warming up zone of 300 metre length is adopted in this study for simulation experiments. Simulation runs are planned at increasing flow levels till flow approaches unstable state. Six series of simulation runs are planned and each series has 8-10 flow levels. It is planned to simulate 1600 vehicles for each run. To eliminate the effect of transient state, the statistics of first one hundred vehicles are ignored.

Performance measures considered for analysis at each simulation run are:- journey speed distribution and acceleration noise of different vehicle types; road concentration (number of vehicles in the road section, road occupancy and influence area expressed as proportion of road area); and overtaking/passing maneuvers executed by different combinations of overtaking and overtaken vehicle types.

The benchmark road with unrestricted road usage for non-motorised vehicles is simulated for traffic composition of level I. The level of service (LOS) is a composite of several operating characteristics that are supposed to measure the quality of service as perceived by the user at different flow levels. The operating characteristics considered to define the LOS are: journey speed of cars and motorised two wheelers; concentration; and road occupancy. Based on the simulation results of benchmark road (Road - I) and traffic composition (Level - I) the levels of service are classified into the four groups (LOS I, II, III, and IV).

The movement of non-motorised vehicles is restricted to only one lane (3.5 m) adjacent to the road kerb. To study the impact of restricting road usage, comparisons have been made with performance measures of benchmark road with unrestricted non-motorised vehicles road usage. To study the sensitivity of traffic composition, the simulation runs for two other levels

(level II and level III) are made and compared with results of traffic composition level I on benchmark road. Simulation experiments are made for three different road widths of 7, 10 and 14 metre. Traffic composition for all the three cases is of level I with unrestricted road usage of non-motorised vehicles.

Mathematical relationships have also been established for various performance measures. Second order polynomials are fitted to relate the performance measures with flow levels.

The study of the simulation results clearly demonstrates the capability of simulation model to simulate traffic over different road widths, traffic compositions, and traffic operating conditions.

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Chapter 1

INTRODUCTION

1.1 GENERAL

India is witnessing rapid urbanisation due to population growth and migration to urban areas. Unequal distribution of economic activities and quality of life continues to attract rural population to urban areas and about 50 million people are being added every year to urban population. National commission on urbanisation (NCU) (Umrigar, 1995) has estimated that by 2001, the urban share of population will be 35 percent and there would be 40 metropolitan areas of population greater than one million and also 440 small and medium size cities with population in the range of 0.1-1 million. The growth of urban population in India has been rapid in the past four decades. The urban-rural population ratio which was 1:9 in 1901 and 1:4 in 1991, is expected to be about 1:3 by the turn of the century. The estimated urban population is 41.7 percent for the year 2011 AD. With changing urbanisation patterns along with socio-economic growth, there has also been a tremendous increase in the transport demand in urban areas. Growth trends in transport demand for selected cities in India are presented in Table 1.1.

There is wide variation in income of urban people, with ownership of non-motorised vehicles (bicycles) and motorised vehicles (auto, 2-wheelers). This results in heterogeneous traffic mix on most of the urban corridors. Table 1.2 presents the ownership of non-motorised vehicles for same selected cities. Twelve major metropolitan cities of India, which have 6 percent of the country's population, account for 30 percent of road accidents. Though urban population is about 30 percent of the total population, but the share of urban road length is only 13.72 percent. Due to this there is high congestion, inadequacy of transport facilities, high accident rates and large delays on urban transport network. It is, therefore, imperative

Table 1.1: Growth Trends in Transportation Demand for Selected Cities in India

City	Total Daily Passenger Trips (millions)		
	1971	1981	2001* (projected)
Calcutta	3.50	11.48	18.89
Bombay	4.60	10.25	18.93
Delhi	1.98	7.00	16.91
Madras	1.60	5.14	9.20
Bangalore	-	3.38	10.78

Source: Gupta (1992)

Table 1.2: Cross Sectional Comparison of Non-Motorised Vehicle Ownership by Households in Indian Cities

CITY	Vehicle Ownership Type (percent households)	
	Bicycles Only	Non-Vehicle Owning
Delhi	23.2	28.5
Ahembdabad	27.1	8.1
Lucknow	30.6	10.5
Madurai	37.9	13.3
Cochin	28.1	23.3
Jaipur	55.0	16.0
Vadodra	48.0	21.0
Patna	43.0	19.0
Nagpur	-	18.7
Hyderabad	-	28.7
Pune	29.1	16.2

Source: Gupta (1992)

to improve the existing urban transportation facilities.

Ribbon development along the urban roads is a common feature in India and this greatly influences the operating speed, delays, acceleration noise, accidents etc (Singh, Kidwai, and Bhattacharjee, 1995). Urban roads, with heavy traffic and demand for better level of service need segregation of non-motorised and motorised vehicles. Another important aspect is the proper planning and provision of facilities and regulatory measures to the users of these urban streets. An adequate level of service would mean the provision of an optimum speed to users; minimum traffic interruptions; safety and driving comfort. In order to select the most beneficial scheme from among the number of alternatives, it is necessary to have an economic appraisal. This neccessiates the availability of reliable information regarding free speed, time delay, fuel consumption, accident rates, and cost of maintenance.

1.2 INDIAN URBAN TRAFFIC CHARACTERISTICS

Most of the cities are having heterogeneous traffic mix of non-motorised and motorised vehicles using same roadway. Table 1.3 indicates modal shares of passenger flows on arterials of selected cities. Wherever the public transport modes are inadequate, share of non-motorised modes is high to cater the transport demand. Thus non-motorised vehicle transport plays a complementary role.

This study is based on a representative arterial of Kanpur. All types of non-motorised vehicles such as bicycles, cycle rickshaws and carts (push carts and animal driven vehicles) are well accepted in Kanpur. The growth pattern of non-motorised vehicles as given in Table 1.4, indicates that for the period 1983-1992, the average annual growth rate of bicycle is the highest (5.3 percent). The growth of animal cart is declining (-0.7 percent), whereas annual growth rates of cycle rickshaws and hand carts are 2 percent and 1.5 percent respectively. Table 1.5 indicates the distribution of person trips by mode and geographic area with in Kanpur. Pedestrian trips account for 42 percent of all person trips. The next two most widely used modes are bicycles (30 percent) and cycle rickshaws (12 percent).

Sarna et al. (1990) have analysed the distribution of work trips with respect to different mode of travel for some selected cities. Results presented in Table 1.6 indicates that 2-wheelers (scooter and cycles) contribute from 25 to 64 percent of travel for work trips. Public transport (bus) share is only 5 percent in Lucknow and 52 percent in Delhi.

Some of the problems of Indian city roads are traffic congestion, road accidents, environment pollution, overcrowding of public transport and poor conditions of pedestrians.

The problems are primarily caused by:

- Uncontrolled access and closely space intersections affect the speed environment and impede flow on urban roadways.
- Encroachment of carriageway: This reduces the effective width of carriageway and reduces the operating speed of vehicles.
- Inadequate regulatory measures at intersections: This leads to more conflicts at intersections.
- Lack of crossing facilities for pedestrians.
- Rapid urbanisation and high growth rate of vehicles increases air/noise pollution and it has also resulted in high growth of accidents..

Table 1.3: Traffic Flow Composition & Modal Share of Non-Motorised Modes on Arterials in Selected Indian Cities

City	Population (Million)	Percent Range in Traffic Composition		Modal Share (in %)		
		Bicycle	Slow Vehicles	Bicycle	Slow Vehicles	Mass Transport Modes
Bombay	8.2	1-11	0-6	na	na	na
Delhi	5.7	10-19	0-14	5	**	62
Ahembdabad	2.5	33-44	0-3	21	**	34
Kanpur	1.7	45-51	15-21	30	19	24
Pune	1.0	na	na	16	**	59
Lucknow	1.0	49-59	9-26	34	19	29
Varanasi	0.8	25-40	23-32	21	20	39
Indore	0.8	30-40	0-3	16	*	54
Madurai	0.8	40-60	6-13	na	na	na
Cochin	0.5	10-13	0-1	na	na	na
Chandigarh	0.4	28-40	8-11	15	4	54
Mangalore	0.3	6-13	0-2	2	**	77
Moradabad	0.3	na	na	25	18	40

* Mostly three wheeled non-motorised cycle rickshaw, ** negligible
Source: Central Road Research Institute, "Transport Flows on Selected Corridors in Indian Cities", New Delhi.

Table 1.4: Number of Non-Motorised Vehicles in Kanpur, 1983-1992

Year	Bicycle	Cycle Rickshaw	Hand cart	Animal Cart/Carriage
1983	315,000	28,000	14,200	5,700
1984	332,000	29,700	13,300	5,800
1985	350,000	31,000	13,200	6,000
1986	371,000	30,500	13,600	6,200
1987	390,450	31,500	13,000	5,800
1988	411,000	34,900	13,500	5,800
1989	432,000	34,800	14,000	5,700
1990	453,000	35,500	14,100	5,450
1991	476,000	31,500	14,450	5,500
1992	500,000	33,350	16,240	5,350
Average Annual Growth Rate Between	5.3%	2.0%	1.5%	-0.70%

Source: Palaniswamy, Singh and Ashfaque (1996).

Table 1.5: Distribution of Person Trips by Mode and Geographic Area in Kanpur, 1987

MODE	CBD Cordon %	Middle Cordon %	Outer Cordon %	City Wide %
Walking	43.4	41.7	43.6	42.1
Bicycle	22.0	27.3	39.8	29.7
Cycle Rickshaw	16.4	12.5	05.5	11.8
Tempo/Auto Rickshaw	1.9	1.5	1.0	1.4
Car	12.2	11.2	6.4	11.2
Motorcycle/Scooter	0.9	1.4	0.1	1.0
Bus	1.8	3.3	2.8	1.5
Train	1.4	1.1	0.8	1.3
Total	100	100	100	100

Source: Association of Metropolitan Development Authorities in Collaboration with Consulting Engineering Services (June 1987), "Traffic & Transportation Study, Kanpur".

Table 1.6: Distribution of Work Trips with Respect to Different Modes of Travel

City	Share for Modes of Travel in percent					
	Bus	Car	Scooter	Cycle	Walk	Other
Delhi	52	15	21	04	06	02
Ahembdabad	16	08	48	16	09	03
Lucknow	05	12	40	21	09	01
Madurai	38	12	28	12	09	01
Cochin	43	16	20	06	13	02

1.3 NEED OF SIMULATION MODEL FOR HETEROGENEOUS TRAFFIC

The complexity of traffic management strategies require that predictive modelling studies be conducted prior to implementation of any strategy. The study of traffic process involves the analysis of the characteristics of individual vehicles in the traffic stream, as well as theoretical and empirical relationships that exist as a result of interactions among the various components. Parameters of particular interest are volume, speed and density, which together describe the quality of service (Whol and Martin, 1967).

Computer simulation models can play a major role in the analysis and assessment of the road transport system and its components. Often these incorporate the other analytical techniques, such as demand-supply analysis, capacity analysis, traffic stream models, car-following theory, shock wave analysis, and queueing analysis, into a frame work for simulating complex components or systems of interactive components (May, 1990). Computer simulation modelling has been a controversial subject due to complex nature of simulation and it should be considered only after analytical techniques have not been found appropriate.

The flow of heterogeneous traffic on urban roads is highly complex and the existing analytical models cannot be used to predict the flow behaviour on urban corridors. A traffic simulation model, which can replicate the movement of heterogeneous traffic, can be used to analyse various operating environment of the road system. Some of the performance measures which need to be estimated with a traffic simulation model are:

- Flow level of heterogeneous traffic handled at different levels of service.
- Time and safety advantage gained by major/minor improvements of the road system.
- Effect of different operating environments

- Segregating motorised and non-motorised vehicles
- Providing separate lanes for public transport modes - buses.

Many traffic simulation models are available for analysing various traffic environments. Both macroscopic and microscopic simulation models have been developed for use at signalised and unsignalised intersections, arterial networks, freeway corridors and rural highways (May, 1990). These models are primarily developed to simulate the flow of homogeneous motorised vehicles. Some models have also been developed to simulate the heterogeneous traffic on rural highways (Marwah, 1976; Ramanaya, 1980; Brodin, 1983). Very limited research has been attempted for simulating heterogeneous traffic on urban corridors (Badrinath, 1990; Hossain, 1996; Hossain and Mcdonald, 1997). The available simulation models have the following limitations with reference to urban heterogeneous traffic:

- **Lane Discipline:** Models simulate vehicles as per specified lane discipline. Vehicles of heterogeneous traffic mix have wide variation of dimensions, do not follow any particular lane concept, and move laterally to optimize road space. Lateral spacing maintained depends upon the vehicle type and operating speed.

- **Conventional techniques and empirical Relations:** Conventional analytical techniques of car-following, shock-wave analysis, queueing analysis etc., do not exactly hold good for mixed traffic.

- **Overtaking:** For "keep to the left" situation, overtakings are executed in the simulation models from the right side. But for the heterogeneous traffic mix, non-motorised and some other narrow vehicles (motorised two wheelers) also overtake from the left side.

- **Yielding and Meandering:** Simulation models generally do not model yielding and meandering phenomenon of non-motorised vehicles.

- **Calibration and Validation:** Models have not been calibrated based on the observed flow process of heterogeneous traffic.

- **Animation and Graphical User Interface:** Simulation models are supposed to help the developer to study the structure of the system being simulated and by doing so better understand the system. The user is also supposed to observe the flow process of the model. But the traffic simulation models generally do not provide aids to the user to observe the flow in simulation experiments. The simulation models behave like

a "Black Box" to the user and provide the final output. Animation of the simulated traffic flow may be highly informatory to the user and the model developer.

1.4 OBJECTIVES AND SCOPE OF THE STUDY

This study aims to model the flow of complex heterogeneous traffic on urban roads in India. Objectives of the study are:

- Study the characteristics of road and vehicle interactions associated with the flow of heterogeneous traffic on urban roads.
- Formulate a simulation model system for the traffic flow process on urban roads.
- Develop a model for animating the flow of simulated traffic. This graphic display may provide an insight into the working of the simulation model and also help to judge the validity of simulation flow process.
- Calibrate the parameters and decision thresholds of various sub-models of the simulation process. This calibration may be attempted by actual field observations and also through simulation experiments.
- Validation to judge the correctness of the model and the various sub-models. Validation process may be attempted through different measures of effectiveness that describe the flow. Comparisons are to be made between the observed and simulated data.
- Sensitivity analysis of various road and traffic characteristics, like road width, operating strategies, traffic composition and flow levels. This may help to define performance characteristics for various levels of service.

Given broad nature of the study and limitations of available resources, the present work is restricted to the following:

- Model simulates only the flow of unidirectional traffic on divided roads.
- Model simulates the traffic only on straight sections with no intersections. The effect of longitudinal gradient is incorporated.
- Field studies to calibrate various sub-models are limited to only two road sections in the city of Kanpur.
- Field observations of the traffic flow to obtain data for calibration and validation are made only on one road section over a seven hour time period.
- Simulation experiments to test the sensitivity of various road and traffic characteristics are attempted for the following:

- Three road widths of 7, 10, and 14 mètre with unidirectional flow.
- Three levels of traffic composition.
- Two different operating strategies
  - restricting the road usage by non-motorised vehicles to certain road width;
  - unrestricted road usage by non-motorised vehicles.
- About 8-10 flow levels for each road being simulated. These flow levels vary from light to very heavy traffic flow.

1.5 ORGANISATION OF THE THESIS

The thesis is presented in 9 chapters. Chapter 2 presents a review of literature on traffic simulation models with special emphasis on the family of models simulating mixed traffic conditions.

Chapter 3 explains the simulation modelling of mixed traffic flow on urban roads.

Chapter 4 gives the detail of graphical package developed for animating simulated traffic and displaying traffic flow parameters.

Chapter 5 explains the traffic flow studies and estimation of various parameters.

Chapter 6 explains the calibration of the simulation model. Three stage calibration process as adopted in this study is explained along with calibration of decision thresholds and parameters.

Chapter 7 explains the validation of developed simulation model. Measures of effectiveness selected for validation are explained. Comparison of simulated and observed values for the each selected measure of effectiveness is explained with the help of frequency distributions and parameters.

Chapter 8 discusses the sensitivity analysis of various road and traffic parameters which has been conducted on calibrated and validated simulation programme system.

Chapter 9 presents the summary, conclusions drawn from the study and suggestions are made for further research.

Chapter 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

Two basic approaches used for traffic modelling are analytical and simulation techniques. Analytical models attempt to obtain solution by means of a limited number of equations. Thus their use is confined to simple traffic engineering problems. Simulation models, on the other hand, attempt to find solutions by means of sequential and iterative application of simple equations and inequalities. The study of traffic flow process can again be said to be either microscopic or macroscopic. A microscopic model deals with the individual vehicle characteristics and its behaviour in the traffic stream. On the other hand a macroscopic model considers the traits of the whole traffic system and the effects of the behaviour of its components on the system as a whole. The availability of digital computers had greatly contributed to the development of road traffic simulation model which are microscopic in nature. The simulation model is capable of representing highly complex traffic systems.

Simulation models have its own objectives, problem solving approach, field of applications and limitation. Traffic simulation is, at the present time, a very dynamic discipline. It is growing fast because it is still a young discipline where dogmas are few and new idea are welcome. It is changing rapidly because it is closely linked with the rapid and continuous advances of digital computers (Radelat, 1981). In the present research simulation approach is applied to the heterogeneous traffic on urban corridors. Therefore, in this chapter review of the literature on road traffic simulation models is undertaken, in order to make study more appropriate and justified. Gaps that exist in these models to simulate the heterogeneous traffic in urban environment are identified.

This chapter is divided into three parts. In the first part, the various analytical traffic flow models are presented. In the second part of this chapter the concept of a simulation as a whole and its need are presented. The rest of the chapter concentrates on the review of road traffic flow simulation models, with special emphasis on models related to urban heterogeneous traffic, as a justification of proposed methodology.

2.2 ANALYTICAL MODELS FOR TRAFFIC FLOW ANALYSIS

The objective of traffic flow modelling is to derive theoretical and empirical relationship between the variables in order to determine the characteristics of traffic stream. The existing literature on analytical traffic flow models can be broadly classified as follows:

- Empirical Model
- Deterministic Model
  - Macroscopic Model
  - Microscopic Model

A discussion on these two categories of models is presented in the following sections.

2.2.1 Empirical Model

In the deterministic approach, algebraic relationship is developed between flow and concentration. Greenshield (1934), one of the earliest investigator in this field gave a relationship between flow and concentration of the form

$$U_s = U_f(1 - \frac{D}{D_j}) \tag{2.1}$$

where U_s, U_f, D, and D_j are average space mean speed, mean free speed, density and jam density respectively.

Greenberg (1959) assumed that theoretical background of high density flow is analogous to continuous fluid flow and based on field studies found that density is a exponential function of space mean speed and speed density relationship is of the form

$$U_s = U_m \log(\frac{D_j}{D}) \tag{2.2}$$

where U_m is the speed at maximum flow.

One of the drawback of Greenberg model is that it breaks at low concentration and this can be verified by putting $D = 0$ in equation 2.2. Underwood (1961) has also proposed a speed-concentration model for the low concentration as

$$U_s = U_f \exp(\frac{-D}{D_m}) \tag{2.3}$$

where D_m is the concentration at maximum flow.

Another single regime model was proposed by a group of researchers at Northwestern Universities (1967) when they observed that most of the speed-density curves appear at S-shaped curve and speed density relationship is of the form

$$U_s = U_f e^{-\frac{1}{2}(\frac{D}{D_m})^2} \tag{2.4}$$

Pipes and Munjal (1967, 1971) have also suggested a general family of speed-concentration models of which linear model is same as model proposed by Greenshield. Drew (1965) has also described a family of models in which Greenberg's logarthimic model is a special case.

To summarize, four single regime models have been developed and tested for freeway data. No model has the capability to track faithfully the measured field data near capacity condition and also each model has deficiencies over some portion of the density range. Due to drawbacks in single regime model some researchers proposed multi-regime model.

Edie (1961) was the first person who proposed the idea of two regime model. Edie (1961) proposed the use of the Underwood model for the free flow condition and the Greenberg model for the congested flow condition. Also Northwestern University research team proposed three multi-regime model formulation.

Relatively less attention has been given to travel time-flow relationships. Travel time-flow relationship which is an empirical model was first demonstrated by Rothrock and Keefer (1957). A number of empirical relationships based on travel time and volume data have been suggested by Guerin (1961) and Norman (1942). They are of the form

$$V = C + bU_s \tag{2.5}$$

Where V is the volume and b and c are parameters. Smeed(1967) and Wardrop(1965) also contributed for developing travel time relationships.

2.2.2 Deterministic Model

Microscopic Model

Car Following Models: A driver reacts depending on the distance he is away from the vehicle in front and its rate of acceleration and deceleration. Car following models are form of

stimulus-response equation. A car following model relates the movement of a single vehicle to the vehicle it follows. Herman and his associates (1959, 1960) at the General Motors Research Laboratories have studied this problem extensively. They assumed that a driver will try to keep the relative speed between his vehicle and that ahead, as small as possible. The mathematical representation is as follows:

$$a_n = K[U_{n-1}(t - T_s) - U_n(t - T_s)] \tag{2.6}$$

where $a_n(t)$, $U_n(t)$, T_s and K are acceleration of nth vehicle at time t, velocity of nth vehicle, time lag or stimulus-response time of driver-car system and driver-sensitivity coefficient respectively. Sensitivity is always inversely proportional to spacing between the two interacting vehicles. Gazis, Herman, and Potts (1959) modified the equation which is as follows:

$$a_n(t) = \frac{K_0}{X_{n-1} - X_n}[U_{n-1}(t - T_s) - U_n(t - T_s)] \tag{2.7}$$

where K_0, X_{n-1} and Xn are constant, position of (n-1)th vehicle and position of nth vehicle respectively.

Continuous examination of the relationship between microscopic and macroscopic models led to generalised form of car following model and it was first proposed by Gazis, Herman, and Rothery (1961). The mathematical representation is as follows:

$$a_n(t) = \frac{K_2 U_n(t - T_s)^m}{(X_{n-1} - X_n)^l}[U_{n-1}(t - T_s) - U_n(t - T_s)] \tag{2.8}$$

where K_2, l and m are constants.

Perceptual factors are related to car following model by Fox and Lehman (1967). Herman and Rothery (1965) extended concept of two car following model to three car following model. Also Fox and Lehman (1965) incorporated the effect of second lead vehicle in their computer simulation models.

There are so many practical applications of the car-following models in different traffic situations. Some of the applications are:

Capacity and Safety of Highways: Bender and Fenton (1972) have used car-following models to study the capacity of highways.

Fuel Consumption and Emission: Chang et al. used car following models to study fuel consumption in different driving environments.

Microscopic Traffic Simulation Models: For example FREESIM, INTRAS, WEAVSIM are, for example, three simulation packages have used car-following modules to describe constrained flow situation.

Mixed Traffic Simulation Models: Instead of the stimulus response based car-following model used in Netsim or Freesim (Federal Highway Administration, 1997), an alternative non-collision behavorial model (CARSIM) (Benekohal and Treiterer, 1988) has been used by Hoque (1994) for traffic simulation of mixed condition (TRASMIC).

Inteligent Vehicle Highway System: The models of car-following are used for calculating longitudinal separation between the vehicles and are used as a longitudinal controler.

Most of the earlier models are deterministic in nature and have ignored the fact that a vehicle is controlled by a human being, who infers actions based on the perceived conditions and vague rules-of-thumb. Chakraborty (1993) proposed an approach, which utilises the concept of fuzzy inference systems to model the process of car-following. Further, unlike the existing models, the process is viewed as a system whose output is determined by multiple stimuli rather than a single stimulus. This departure in the structure and the use of the fuzzy inference system make the model more realistic.

Macroscopic Model

The behaviour of traffic at bottleneck appears to be acting in a shock-wave like manner. Analogies have been drawn between the flow of fluids and the movement of vehicular traffic. Richards(1956), Greenberg (1958), and Lighthill and Whitham (1955) are one of the major contributors in this field. Lighthill and Whitham (1955) also analysed several traffic flow problems based on the theory of shock wave. The basic assumption is that high density traffic behaves like a continuous fluid. Here, the fundamental equation is that one that expresses the conservation of matter.

$$\frac{dU_s}{dt} = -\frac{c^2}{D}\frac{\delta d}{\delta x} \tag{2.9}$$

where U_s, D, x, t and c are fluid velocity or space mean speed in kmph, Density in vehicles per km, distance in kms, time to travel distance x and roadway parameter respectively.

The solution of Eq. 2.9 gives the space mean speed is a function of density as follows

$$U_s = c(log(D_j) - log(D)) \tag{2.10}$$

where D_j is a jam density in vehicles per km.

Richards (1956) has implied transfer function as $\frac{-A^2}{D}$ where A is a constant having dimension of speed concentration. Richards (1956) yields the relation which is same as Greenshield's model of Eq. 2.1.

Pipes (1967, 1969) has generalized Richards model by taking equation of state as

$$F = -A^2 D^{2s+1} \tag{2.11}$$

where s is an integer not equal to -1. Solution of Eq. 2.11 gives the expression of space mean speed, which is as follows:

$$U_s = U_f[1 - \frac{D}{D_j}^{s+1}] \tag{2.12}$$

Prigogine (1961) suggested an analogy between traffic and gases. Prigogine and Herman (1971) in their paper discussed the development of theory, assumptions and they have taken some numerical applications in order to explain the concept. They had divided multi-lane traffic into three separate processes. These are as follows:

- relaxation process or speeding-up process;
- the interaction process, or the slowing down process;
- the adjustment process.

These process are expressed in a kinetic equation:

$$\frac{df}{dt} = \frac{\delta f}{\delta t} + u(\frac{\delta f}{\delta x}) = (\frac{\delta f}{\delta t})_{relaxation} + (\frac{\delta f}{\delta t})_{interaction} + (\frac{\delta f}{\delta t})_{adjustment} \tag{2.13}$$

2.3 TRAFFIC SIMULATION

Naylor et al.(1966) suggested that simulation may be defined as, "a numerical technique for conducting experiments with certain types of mathematical models which describe the behaviour of a complex system on a digital computer over extended periods of time". Mize and Cox (1968) proposes that it is a process of conducting experiment on a model of a system. Whol and Martin (1967) describes simulation as an imitation of real situation by some form of a model that assumes the appearance without reality.

According to Hurley and Radwan (1981) traffic simulation computer program have long been viewed as practical and effective tools for analysing traffic flows, especially when one considers the expense and time required to collect and analysed field data. In addition to being used for operation purposes, some of these programs, especially those based on microscopic flow simulation, have been used for research.

There are generally a number of steps in simulation of an engineering system. Though the details may vary from time to time, a number of steps are common from time to time, a number of steps are common to several simulation studies. Naylor, Balintfy, Burdick, and

Kong (1966); Mize and Cox(1968) described the various steps for simulation process. It was further modified by May(1990) and divided simulation into eleven elements.

2.3.1 Traffic Simulation Approaches

Traffic simulation models can be either microscopic or macroscopic in nature.

Macroscopic Approach

This approach represent the traffic in some aggregated form, these models are usually less accurate but involves less computational time and cost.

Microscopic Approach

In this approach simulation models describe the detailed time-varying trajectories of individual vehicles in the traffic stream. The microscopic approach offer a much better way of considering the high variation of vehicle characteristics such as acceleration and deceleration capability (power mass ratio), dimensions, desired speed and also extensive interactions among vehicles in heterogeneous traffic streams, predominant in most of the developing and under developed countries. Because of this in the present thesis work microscopic approach has been adopted.

Depending upon type of traffic mix to be simulated, simulation models can be divided into homogeneous and heterogeneous (mixed) traffic simulation models. Depending upon traffic flow pattern, simulation models can also be divided into lane based and non-lane based flow simulation models. The available simulation models can be classified according to their areas of application (TRB, 1981). The classification are as follows:

- Intersection models
- Arterial/Highway models
- Network models
- Freeway models

2.4 SIMULATION MODELS FOR HOMOGENEOUS TRAFFIC

Of other theories which deduce the properties of a traffic stream from the behaviour of the vehicles of which it is composed are those due to Schuhl(1955) and Kometani (1955). Haight

(1963) has given a brief general survey of the literature on traffic theory Schuhl for example, considers a two lane road in which the sole constraint to free speed(the distribution of which he assumes to be known) is the passing manoeuver. For most of his work, Schuhl confines himself to averages although he does allow negative exponential gaps in oncoming traffic. In particular, he assumes that cars in the same direction are overtaken at free speed and at equally spaced intervals

When multiple objectives and constraints are come across in modelling a traffic stream simulation modelling may be resorted to. The behaviour of individual vehicles is described by the models developed. Important manoeuvres take following and overtaking as described by these Submodels. Most of the simulation models developed cater to either single lane or two lane roads, a few of which have been mentioned below.

Gerlough (1955) made a pioneering attempt to model the freeway traffic. Shumate and Drikson (1965) developed model by considering a Poisson distribution for headways and a normal distribution of desired speeds by drivers. They also included a probability function to decide a gap acceptance by a driver wishing to overtake.

One of the first microscopic analytical model was formulated by Tanner (1959) who derived an expression for the mean speed of a fast vehicle in a slower traffic stream on a two lane two way road. He computed the mean speed and minimum spacing of vehicles in the stream which arrive at random.

A traffic simulation model for an urban road was developed by Stark (1962). Blunden and Pretty (1964) also conducted studies for the analysis of traffic flow using simulation technique. Of the macroscopic models developed, Miller (1965) developed a model for the behaviour of traffic on a two lane two way road. He considered (i) queueing on roads when limited overtaking is possible; (ii) queueing before overtaking; (iii) queueing when overtaking is not possible. Analytical models involve formulation and solving of equations to represent the behaviour. This becomes increasingly difficult when an attempt is made to greater levels of detail in the traffic flow process.

Little (1966) used mixed integer programming technique for set up the computational of optimal offsets among the traffic signals of urban arterial system. To obtain signal progression two arterial model SIGART (1967) and SIGPROG (1967) are developed; both the models are macroscopic, deterministic optimization models with periodic time scan.

Warnshuis (1968) in his paper has given the detail of digital simulation modelling of two dimensional urban expressway. Warnshuis (1969, (a), (b), (c), (d)) described the structure of model and program listings of SDC model.

Three stochastic inputs were considered by the model developed at North Carolina

State University (Hiembach, Horn, Khannabis, and Chao, 1972) namely desired speed of the vehicles, the headway distributions and the overtaking behaviour given a gap acceptance or rejection. This model was time scan oriented. Hsu and Munjal(1974) reviewed 15 simulation models associated with freeway traffic and compared the models with eight desirable features.

In a review of models for traffic the TRB special report 194 on "The application of Traffic Simulation Models" locates a total of 104 distinct computer models that could be applied to traffic engineering problems. The models can be classified based on the geometrics that the model analyses, as, Intersection models, Arterial models, Network models and Freeway models (Gibson, R.P.David 1981). Some of the potential models discussed in TRB (1981) are: MRI (St. John, Kobett, Sommerville, and Colanz, 1970) for analysing traffic flow on hilly terrain; SUB (1973) has been developed to evaluate urban bus operation; PASSER-II (1974-78) for signal progression; PASSER- III (1974-78) for signal timings on diamond interchange; SIMTOL (1976) for trucks on grades. Some of these models are discussed below.

The microscopic and stochastic model MRI (St. John, Kobett, Sommerville, and Colanz, 1970) has been developed to evaluate the traffic characteristics of roadways in hilly terrain. The geometric configuration of the model allows simulation of directional flows on a four lane, divided roadway with intermittent hill-climbing lanes. It has been assumed that desired speed follows normal distribution; speed and acceleration characteristics are function of grade and horizontal curvature. The probability of accepting an overtaking opportunity are related to the speed of the lead vehicle and passing opportunity distance.

Passer-II model (Messer, Haenel, and Koeppe, 1974) is a macroscopic, deterministic optimization model designed to analyse individual signalized intersection operations or to determine optimum progression along an arterial street considering varied multi-phase signal sequences. Computational methodology of the model is a time series search and find optimization. The model PASSER-III (Messer et al., 1976; Fambro et al., 1976) has been developed to determine the optimal offsets between the two signals of diamond interchange which minimizes total interchange delay for a given cycle length.

Event based simulation model was developed by the German model (Brilan, 1974; Wiedman, 1974) which considered traffic processing on a service counter basis. This was done for a straight section, for a two lane highway with two way traffic. Martin and Wohls associates 1975 reviewed the North Carolina state university model. In all these models not much attention was paid to the composition of the traffic.

Akonteh (1977) developed a model which is based on a simple relationship involving driver behaviour, acceleration/deceleration, car following function and kinematics or force equations. In the model it has been assumed that acceleration at any instant of time is a

function of vehicle speed, driver behaviour, and position of the vehicle with reference to the road geometry and other vehicles. The free speed is defined only for level tangent section and while overtaking model is deterministic in nature.

For network simulation microscopic simulation model NETSIM (Liberman et al., 1977-79) was developed for arterial networks. NETSIM simulation model have a capability to animate simulated traffic on road network and also it contains user friendly graphical routine to display statistics of traffic parameters and other outputs obtained from the NETSIM. Apart from that there are large number of macroscopic models were developed, including SIGRID (Tr. Res. Corpn., 1965), SIGOP (Tr. Res. Corpn. U.S.A., 1965-66 and Peat, Marwick, Livingston & Co., 1968), SIGOP-II (FHWA, 1974), SIGOP-III (FHWA, 1982), MITROP (Gartner, Little, and Gabbey 1975-76), SCOOT (Hunt, Robertson, Bretherton, and Winton (1981); Ferranti, GEC and Plessey Co., 1981), SSTOP(1979) and TRANSYT(1987).

Microscopic and macroscopic computer simulation model have been developed for freeway corridor simulation also. The INTRAS (Wicks and Liberman, 1980) model is the only microscopic simulation model for freeway simulation. There are several macroscopic freeway simulation models which includes CORQ (Yagar et al., 1986), FREQ (Stock et al., 1973; May et al., 1988), FRECON (Campbell et al., 1984) and KORNOS (Plum et al., 1985) models. Also extensive review of literature of freeway simulation model is given in May(1981) paper.

A number of simulation tools, mostly developed one or two decades ago, exist for assisting the testing, verification, and improvement of traffic mangement strategies has been described by Koutsopoulos and Yang (1992) in a literature review paper. However, none of these models can effectively meet the requirements of simulating large-scale traffic networks for ITS applications, especially at an operational level. At present some of the models undergoing extensive updating and enhancement (Santiago and Kanann, 1993). As we know that emerging ITS technologies add new functionalities in traffic mangement systems, such as mainline traffic control, real-time route guidance, and incidence management. New traffic simulation models have been developed or are under development for ITS applications. Examples are DYNASMART (Jayakrishnan et al., 1995; Mahmassani and Jayakrishnan, 1991), INTEGRATION (Van Aerde and Yagar, 1988) and THOREAU (Codelli et al., 1992). The simulation model in DYNASMART and INTEGRATION is mesoscopic, designed mainly for traffic management applications. THOREAU is a microscopic model developed for evaluation. However, it has a very long running time. Other microscopic models are also under development for modelling Automated Highway Systems (Eskafi et al., 1996). Qi Yang and Koutsopoulos (1996) developed a microscopic traffic simulator for modelling traffic networks with advanced traffic control, route guidance and surveillance systems.

2.5 SIMULATION MODELS FOR HETEROGENEOUS TRAFFIC

One of the earliest models that takes into consideration the mix of vehicle types in the traffic stream was the model developed by Marwah (1976) who simulated mixed traffic considering six different types of vehicles on a level tangent section of a two lane two way road. This model studies the interactions between vehicles at different volumes and compositions of traffic. Model was successfully calibrated and validated on urban road stretch of Kanpur city.

The Swedish (Gynnerstedt, 1977, 1979) model considers traffic flow on a highway by considering a large number of overtaking manoeuvres, desired speed related to road width, horizontal curvature, speed limit and gradients. This model has been designed for mainly heavy traffic on an event scanning basis. Model has a capability of simulating heterogeneous traffic and also after modification, it has been applied to simulate traffic mix containing non-motorised vehicles. This model needs a large amount of input data and is in the preliminary stages of validations. The two lane bidirectional traffic simulation model (VTI) primarily aimed for simulation of homogeneous motorised traffic, which has been generalised with regard to heterogeneous traffic in India (CRRI, 1985 (a) and (b)). It has also been extended to simulate a traffic on a larger range of road widths and terrain conditions by two different model versions - one version developed for narrow roads where the crossing interactions between vehicles in the opposing streams are the predominant traffic congestion factor (Palaniswamy, 1983 and Brodin and Palaniswamy, 1985); second version aimed for wider carriage ways where the crossings are generally neglected, and includes auxiliary lanes (Marwah, 1983). Chelapathi (1987) further modified Indo-Swedish traffic simulation model (VTI) for simulating urban multi-lane unidirectional homogeneous traffic. This model is also based on Swedish model (1983) which has earlier been modified by Marwah and Palaniswamy to accommodate single lane, two lane and four lane traffic situations with varying shoulder widths. Model estimates the effect of traffic congestion and road geometry on operating speeds. The logic incorporated utilises Highway Design Model (1985) (HDM) to quantify road user costs for various alternate highway conditions. The simulation model is more akin to automobile traffic situation, as the lane change follows with certain probability.

Further, Ramanayya (1980) developed a simulation model for simulating heterogeneous traffic on single lane and two lane one way and two lane two way roads. Model was successfully validated on the field data collected in the Hyderabad city. And also it was found that PCU value of vehicle is not a constant quantity, it is a function of traffic composition, road

width and flow rate. Further, Ramanayya (1988) modified his original developed model for different operating conditions and traffic mix.

Tuladhar (1981) studied urban traffic system and developed multi regime models for volume-density, speed-flow and speed-density relationships. The main deviation of this modelling is to split the road into equal segments of one metre width and model the flow. This was done with a view to accommodate smallest sized vehicle like bicycle. Large sized vehicle will be occupying more than one strip width where as small sized vehicle will occupy only one strip width and the relationships are likely to get biased because of this intermixing.

Road user cost study (RUCS, 1982) was conducted in India by CRRI in collaboration with MOST (Ministry of Surface Transport, India) and World Bank. Parameters like fuel consumption, speed, roughness etc., were collected for single, intermediate, double and multi-lane divided roads for different types of shoulders. Based on the information, empirical speed-flow relationships were developed and tentative guidelines were proposed for rural traffic situation. The study is mainly empirical in nature.

Vidyadhar N. Kulkarni (1982) developed a macroscopic model for simulating urban traffic flow. The model was programmed in universally accepted Fortran IV language and for generating vehicle flow characteristic Simula programming language has been used and the GPGS (General Purpose Graphic System) package was used in plotting time-space diagram of vehicles. The model simulates a divided city road of 7.25 m width. In this model lane concept has been used for representing the simulated road stretch and in the present model extra lane has been provided for non-motorised vehicles. Seven categories of vehicles namely bus/truck, motor cycle/scooter, car/tempo, cycle rickshaw and bicycle are included in this model. Vehicle characteristics like arrival time, free speed, arrival gap, lane and flow status are generated by the model based on the arrival gap distribution, speed distribution, traffic volume and composition. The traffic flow is divided into free flowing, following started, already following, merging and following terminated logic. All vehicles in the model are simulated with the help of periodic scanning technique. Overtaking and yielding logics of the vehicles are modelled by using concept of available time gap for merging and diverging. Model was validated on one urban road section for space mean speeds of cars only. Model lack in field studies, because of that certain assumptions were made for modelling traffic operations and vehicle manoeuvers.

Bandyopadahyaya (1984) developed a model for simulating traffic on metropolitan road system in India. He considered urban road system in the city of Calcutta, which has four lane wide road with the two-way movement. Two tram tracks, one for each direction of flow, is embedded in the central portion of travel way. The road system is divided into

small homogeneous road block. The traffic is generated randomly and the simulation model system includes: Free Flow model, Vehicle Interaction Model, Fuel Consumption Models and an approach for selection of best signal settings. Model was validated and calibrated on road section having signalized intersections and vehicle stops.

Model developed for mixed flow traffic for Indian conditions was for two-lane and multi-lane highways (Palaniswamy, Gynnerstedt, and Phul, 1985). This stochastic, discrete-event based simulation model was based on modifications made to the Swedish Road Traffic Simulation Model (SWERTS), designed for motorised traffic. The model was modified to simulate Indian roadway an traffic conditions including narrower, bi-directional roads with widths varying from 3.75 m to 7 m, different shoulder types, alignments, terrian, desired speed, power-to-mass ratio, overtaking gap acceptance and yielding probability distributions, and passing speeds.

Gupta and Khanna (1989) studied the effect of one vehicle on the other in the urban mid block conditions. Notable features of this model is determination of interactions between pairs of vehicles while they are moving. To obtain the effect of one vehicle on the other, time lapse photography technique was used. In this study the proportion of cycles are found to be between 60 to 72 percent while scooters are upto 25 percent and cars from 1 to 2 percent. Lateral spacing between several pairs of vehicles were obtained, for cycle-cycle, cycle-cycle rickshaw, cycle-two wheeler, two wheeler-two wheeler and like wise.

Badrinath (1990) developed a simulation model for simulating urban traffic. The present work was the extension of MORTAB project done by Ramanayya (1980). Further, Sutomo (1992) developed a model for micro-simulation of mixed traffic at signalised intersections. In this model, new concept has been used for representing the roadway. Hoque (1994) in his intersection simulation model has used the same concept (Sutomo, 1992) for road representation and the model was validated for traffic data at signalised intersection in Dhaka city.

The earliest simulation models developed for homogeneous traffic conditions, such as TRAFFICQ, were based on simple principles. Two recent studies have been performed for mixed traffic conditions using such models. In both these studies, vehicles arrivals were simplistically modelled using appropriate arrival distributions (exponential and negative exponential). Vehicles were allowed to proceed through the intersection based on the availability of gap in the opposing traffic flows. In the first study (Chari, Badrinath, and Murthy, 1993), the interaction between pedestrians and vehicles was also considered. The second study [Agarwal, Gupta, Jain, and Khanna, 1994), reported promising results in the comparison of observed and simulated time headways, in which the differences ranged from approximately

two to ten percent. However, both the papers provided few details on the actual simulation of the traffic, and how the mixed flow components were modeled. Thus, although the results of these studies appear to be convincing, the applicability of such simulation models appears to be fairly limited.

Raghvachari (1995) given a brief review of traffic simulation models for mixed traffic flow. He also discussed applications of some of the simulation models (MORTAB, UTSM) in transportation planning for Indian conditions.

Hossain (1996) developed a micro-simulation model MIXNETSIM for simulating mixed traffic on urban networks. Validation process of the model has been carried out in the City of Dhaka, Bangladesh. It was found that model replicates real life traffic operations and vehicle manouevers.

Khan and Maini (1998) reviewed some of the models related to non-lane based heterogeneous flow condition. They have concluded that a uniform definition of passenger car equivalent will not be applicable- the values of equivalency will depend on the traffic composition, and will increase with increasing traffic density. The right turn factors (for left hand driving conditions) were found to be higher than the left turn factors. The performance of vehicles in mixed flow depends in varying amount, on the intersection geometry, prevailing traffic conditions, and the static and dynamic properties of vehicles.

Khan and Maini (1998) also observed that there is a need to explore how and when traffic streams may be characterised as heterogeneous, and when these models are best applied. This will allow more of the techniques developed to be transferable to locations beyond the ones for which they were developed.

2.6 DESCRIPTION OF SOME MODELS FOR HETEROGENEOUS TRAFFIC FLOW

2.6.1 Simulation of Mixed Vehicular Traffic for Indian Conditions

Studies in stochastic modelling and simulation of mixed vehicular traffic for Indian conditions with special reference to Kanpur metropolis have been done by Marwah (1976). This study considers the nonlinear interactions between two different vehicles in mixed traffic flow situations and attempts to characterise the variations of passenger car equivalents (PCES) in terms of traffic composition and volume. Computer simulation is adopted in this study to analyse the mixed traffic flow and infer the PCES under different volumes and composi-

tions of traffic. Using historical monthly and daily traffic data of seven years on five main highways approaching Kanpur, stochastic models have been developed for the monthly and daily traffic data for three categories of goods carriers viz., incoming motor vehicles, transit motor vehicles and incoming slow moving vehicles.

A computer simulation model of mixed traffic flow on a two lane highway was formulated. Vehicles moves from either direction of the roadway section and scanning done at fixed time intervals. Separate submodels have been developed for the free flowing, constrained flowing, overtaking and yielding sequences. Initially historical data of arrival times, traffic composition and system parameters were used to identify the system and validate the system model. Simulation runs were also performed for the following cases:

(i) Homogeneous traffic at different volumes for passenger cars and trucks taken separately.

(ii) Mixed traffic at varying volumes and traffic compositions for the following cases:

   a Five cases consisting of two types of vehicles only, including passenger car and one of the other vehicles viz., truck, motor cycle/scooter, horse driven vehicle, bullock cart, or bicycle;

   b four cases consisting of combination of three vehicles including car, truck and one of the remaining four categories of vehicles; and

   c all the six types of vehicles at the peak hourly compositions only.

It was inferred that when traffic is homogeneous, the vehicles move essentially at their free speed at low volume levels. As the volume increases, the headways are reduced and there is a significant reduction in the operating speed of the vehicles till at a certain volume level, the density of the roadway section continues to increase thereby jamming the traffic. There is a nonlinear relationship between the volume level and the average operating speed of the vehicles.

In the case of mixed traffic flow, the effect on the operating speed of passenger cars was studied at varying traffic volumes and composition. The operating speed of the car in the mixed flow reduces even at low volume levels due to restrained overtaking operations. The operating speed was also found to vary with the composition of slow moving vehicles in the mixed flow. Other vehicles affect the operating speed of cars and PCES were estimated for combination of two or three types of vehicles at different volumes and compositions. The PCES so determined were not constants, but found to vary non-linearly with the traffic volumes and compositions.

In another study Marwah (1983) developed a simulation model for two lane and four lane highway for Indian traffic conditions. Simulation model consisted of different types of slow and fast vehicles on two and four lane highway systems. The model was validated based on data collected for different measures of effectiveness (MOE) like travel times, spot speeds, time headways, number of overtakings and passings for different vehicle types. For testing the sensitivity of model, test runs were made for two lane and four lane highways in plain terrain under different volume levels.

2.6.2 MORTAB (Model for Road Traffic Behaviour)

MORTAB model was developed by Ramanayya (1980) in which the concept of "Equivalent Design Vehicle" in place of Passenger Car Unit has been used. For simulating traffic on single lane one way, two lane one way and two lane two way roads models have been developed, which are named as MORTAB-I, MORTAB-II, MORTAB-III. These models have a capability of simulating eight different classes of vehicles namely car, bus, truck, auto rickshaw, motor cycle, cycle rickshaw and animal driven carts simultaneously. Platoon and bunch formation of bicycles, cycle rickshaw and scooters/motorcycles is considered while modelling. And also the models take care of overtaking operation without reduction in speed by using the concept of lateral clearance thereby introducing a new dimension in mixed traffic flow operations. Minimum spacing required by two successive vehicles moving in the traffic has been formulated to take into the account the random behaviour of drivers. A number of experiments have been conducted in order to validate the model. Data used in validation process was collected at Hyderabad city. Further experimentations have been ~~done~~ conducted on the models by varying traffic volumes from 100 vph to 800 vph and percentage of slow moving vehicles (non-motorised vehicles) have been taken from 10 to 50, which yielded valuable information on speed flow, speed density and flow density relationships.

In the simulation model three levels of service A, B and C has been taken. Level of service in the model was ~~being~~ defined as percentage reduction from the desired speed such as 5 percent for A, 15 percent for B and 25 percent for C. Further, Ramanayya (1988) in his study claimed that PCU of a vehicle is a function of traffic composition (percentage of non-motorised vehicles in traffic mix) and roadway width.

Equivalent Design Vehicle Unit (EDVU) concept

Experiment with MORTAB have shown that the passenger car like any other vehicle is affected due to mixed stream operations. The characteristics of a car do not remain as that of car in the presence of other types of vehicles. In the proposed approach, attempt has been made to convert all types of vehicles including the passenger car into as "Equivalent Design

Vehicle Unit". Comparing the values with those reported in Highway Capacity Manual "EDVU" has been obtained for all types of vehicles considered in the simulation model. It is found that value of EDVU varies from one level of service to another. In other words, it can be said that EDVU is a function of traffic composition and flow rate.

2.6.3 UTSM (Urban Traffic Simulation Model)

UTSM model was developed by Badrinath(1990) for simulating urban mixed traffic situation in Hydrebad city. In the UTSM concept of group size has been used to define level of service in heterogeneous traffic flow situation. UTSM is a continuation of MORTAB project, suitable for urban areas containing heterogeneous traffic. Field studies through video graphic techniques have been conducted at several locations in Hyderabad city, which enables to understand headway, lateral positions, speed, composition in a better manner. Heterogeneous traffic is generated in this model by considering 5-different distributions with switching at appropriate levels of volume. The vehicles present in mixed traffic are further reclassified into four wheelers fast, two and three wheelers fast and two and three wheelers slow in order to curtail the data requirement.

A new approach "Information theory logic" has been applied to model overtaking and passing manoeuvers in mixed traffic flow situation, In this approach, the driver is expected to perceive the number of bits of information in the vision zone and if the total bits of information are within the permissible limits, the driver will go ahead without reduction in speed and overtake the slow moving vehicle (flying overtaking). This logic was further extended by considering lateral placement, reactions etc.

The UTSM has been successfully validated for mixed urban traffic. After successful validation, UTSM was used to draw various conclusions. The UTSM was studied by varying the traffic volume level between 200-2000 vph, road widths between 3.5 to 6.5 metre and composition of 4-wheelers from 10-50 percent.

The results from various simulation experiments have indicated that drivers in mixed traffic start positioning themselves across the road based on the magnitude of the threat to which they are exposed. Drivers do not hesitate to position themselves across the road with certain longitudinal overlap or abreast while moving along the road. This concept is termed as "Cluster" or "Group".

For estimating level of service concept of groups has been used in place of vehicle speeds. The entire traffic flow in urban areas is proposed to be divided into four classes depending upon percentile values and group sizes formed. If the observer finds that the headway between two vehicles is less than about 2 seconds, they are said to be travelling in a group.

The number of consecutive vehicles having less than above said headways are said to be in a group. Level of service with the help of group sizes can be defined in the following way:

LOS A If the group size observed is less than 6.

LOS B If the group size is greater than or equal to 6 and less than or equal to 10.

LOS C If the group size is greater than 10 and less than or equal to 13.

LOS D If the group size is greater than 13.

Development of Animation programme for animating simulated traffic by UTSM is in under progress, And also work related to adding other extra graphics facility for displaying traffic flow parameters and UTSM outputs is in progress. Incorporating pedestrian traffic and side interferences into the UTSM model logic to replicate urban scenario is another direction where further research is under progress.

2.6.4 TRASMIC (Traffic Simulation of Mixed Condition)

Model for microscopic simulation of mixed traffic flow at signalised intersection was developed by Sutomo (1992). Sutomo named his model as TRASMIC (Traffic Simulation of Mixed Condition) in which strip approach has been used in place of lane approach used in most of the models. In the strip approach road width is divided into strips of smaller width (in this case strip width is taken as 1m). Therefore, a lane analogy was adopted to strips. In the strip approach, lateral movement is simulated by allowing one strip width of a lateral movement within a time interval. But, in the real life urban road system there is no strip marking and normally the amount of lateral width movement at a certain time depends on vehicle's requirement. In this study, it was found that passenger car unit (PCU) value changes with change in traffic mix and also it is dependent on flow rate.

2.6.5 MIXSIM (Mixed Traffic Simulation Model)

Hoque (1994) developed a micro-simulation model, MIXSIM, for simulating traffic at isolated signalised intersections with mixed traffic conditions. In this model, strip based approach has been adopted for representing the road, which was taken from the TRASMIC model to replicate the urban heterogeneous traffic flow mechanism at the signalised intersection. In the MIXSIM model narrower strips of width 0.5 m has been taken, which enables to reduce the accompanying error in calculating lateral movement and model the turning movements and other conflict situations at an intersection. In the microscopic simulation models such

as NETSIM or FRESIM (Federal Highway Administration, 1997) for lane-based traffic, a list of all vehicles in a link, within a lane is maintained. Given that vehicles can occupy several strips, and therefore are part of several lists - a global vehicle list is maintained for each approach, based on the entire width of the road. For each vehicle in a system, information tracked included front-left, front-right, rear-left, and rear right. Instead of the stimulus-response based car-following model used in NETSIM or FREESIM (Federal Highway Administration, 1997), an alternative non-collision behavioral model (CARSIM) [Benkobal, 1986; Benkobal and Treiterer, 1988] was adopted. In the non-collision based model constraints of maintaining a safe distance is used, and therefore the following vehicle always considers the speed and the maximum deceleration rate of the precceding vehicle and keeps track of the target position of the stopping vehicles. Because of the mix of vehicles of widely varying operating characteristics, it was determined this approach provided better results than the stimulus-based approach. Signalised intersections in Dhaka city have been considered for calibrating and validating the model. During experimentation it was found that there cannot be a unique PCU values for vehicles in mixed traffic stream. It was inferred from experiments with the model that PCU values of vehicles depends upon road width, traffic composition and flow rate.

2.6.6 MIXNETSIM (Mixed Traffic Network Simulation Model)

Hossain and Mcdonald (1996, 1997) developed a micro-simulation model MIXNETSIM (mixed traffic network simulation) which would be able to simulate the traffic operations in urban networks/corridors of developing cities. A co-ordinate approach to modelling vehicle location was adopted in order to be able to replicate the non-lane based flow characteristics of developing cities traffic. Each road vehicle is modelled by incorporating both drivers' behaviour and vehicle characteristics with most of the related attributes. The model was calibrated and validated against the video and manual data collected for Dhaka City in Bangladesh. It was found during the validation process that the modelling approach and the logic were working as intended. The animated view of simulated traffic flow through the network under consideration can help model users to understand the simulation process on urban network and it also helps programmer to calibrate and validate the model. The simulation experiments result indicate that that the performance of motorised vehicles deteriorates because of mixing with non-motorised vehicles. With a right turning movement/ban on non-motorised vehicles, the performance of motorised vehicles improve significantly.

2.7 INTERACTIVE COMPUTER GRAPHICS INTERFACE FOR TRAFFIC SIMULATION MODELS

The STARK/NBS (Gibson and Ross, 1977) model is a detailed simulation model that uses deterministic vehicle manoeuvers and traffic behaviour rules including.such factors as lane-changing logic, gap acceptance, right-of-way, and car following. The model has a capability of producing animated display of simulated traffic. This helps the model to replicate the real life traffic situation.

The Aerospace Corporation Model VPT (Vehicle Performance in Traffic) (Gibson and Ross, 1977) is an exceptional detailed microscopic network simulation model. In the model there is a facility of movie representation of simulated traffic flow on the network.

NETSIM (FHWA, 1980) is an extension of the UTCS-1/SCOOT model. The model is a microscopic simulation, dealing with the movement of individual vehicles in an urban street network, according to car-following, queue discharge, and lane-changing theories.

Joline (1976) of Aviation Simulation International developed a movie presentation of the UTCS-1 model that displays the movement of individual vehicles with an urban network. This work has been useful in demonstrating the relationship among traffic flow patterns and signalization timing and illustrating the model's functions and utility to potential users. This also helped in debugging the program system and also identify errors in the model that have led to various modifications.

The emergence of a graphics standard known as the Graphics Kernel System (GKS) leads to development of Netsim graphics system. Eiger, Chin, and Woodin (1979) have developed a program, GRNAT, that generated NETSIM-based passive displays of animated network vehicle flows on a CRT. With the help of graphical software modifications of the network geometry or related parameters can be easily accommodated. Such type of animated displays can be used in searching for high-performance traffic management strategies. Subsequently, a revised program NETSIM/ICG (Chin and Eiger, 1981) has been developed that can provide both real-time and passive animation of traffic flow. Furthermore, the animated queue length display is also provided by NETSIM/ICG. With this capability, the traffic engineer can obtain similar information as animated traffic flow but with less computation and display.

Schneider, Combs, and Folsom (1980) have developed the NETGRAF system, which is a graphics system designed to aid the use and interpretation of NETSIM results. The measures of effectiveness (MOE) can be displayed for one simulation run or MOE of different

simulation runs can be compared without any difficulty.

The ITDS (Roberts, et al., 1985) and INTRAF(Andrews, et al., 1984) software enables users to enter data to the Netsim model in a "friendly" interactive mode.

The Netsim graphics software named GTRAF, is designed to provide information rather than data, and insight rather than statistics alone. GTRAF was written in FORTRAN programming language and it was developed on an IBM PC AT equipped with the IBM professional graphics controller and color monitor. The Netsim simulation program and the GTRAF graphics software are two independent pieces of software. Some of the outputs of main Netsim simulation model is input to the GTRAF.

Parakh (1977) also developed a interactive computer graphics software to improve the analysis of ~~a~~ large-scale flow problems by visually displaying the output of a computer simulation. His Graphical Interactive Traffic Simulation (GRITS) a deterministic platoon-level model, can produce local global displays of simulated network traffic. More specifically the program has the capability to display, at each intersection, the three dimensional plots of MOEs as a function of signal split and cycle time.

In the same way, Schnieder, Jette, and Lewis (1980), and Schneider and Jette (1979) also developed a graphical user interface for FREQ freeway simulation model, which was named as FREGRAF, which is a computer graphics program to aid the use and interpretation of a macroscopic freeway simulation model FREQ6PE.

Indian Traffic Simulation Model (CRRI, New Delhi; IIT, Kanpur; 1997) named as IT-SIM. Ramesh (1991) developed a sub-model named as junction process for simulating the movement of vehicles at signalised and unsignalised intersections. The developed model also has facility to animate simulated traffic flow and time space diagrams. Overtaking sub-model of ITSIM takes care of static and dynamic friction along the flow (Suresh, 1991). The model simulates traffic flow and records each event in chronological order in an event file. System of visual displays developed by Ramesh (1991) and Suresh (1991), which are the part of ITSIM helps user to quickly evaluate and assimilate information. The graphical system of ITSIM contains two major program systems.

- Animated display of traffic flow.
- Time-Space trajectories of simulated traffic flow.

There are two types of animation programs in ITSIM (Marwah, 95).

a) **Event Oriented Animation of Traffic Flow** The program represents simulation output either in one view port or in multi-view port. It shows the display of traffic flow

at every event occurring time. The program moves simulated traffic at variable time intervals.

b) Uniform Time Interval Animation The program shows the desired part of the road stretch in desired number of windows. The displayed road system is displayed into four lanes. The program displays the simulated traffic at uniform time interval, which gives the feel of continuous movement to a viewer.

Time-space diagram has also been developed by Marwah (1995) for ITSIM. Graphic model shows road geometry of the current observation stretch in multiple windows, which include road stretch along with animated traffic flow and plots (time space) diagram in other window by taking time on X-axis and length of the road on the Y-axis.

Singh (1998) developed a graphical display system (GDS) used for visualization and analysis of output results of Indian Traffic Simulation Model for Two Lane and Four Lane Highway called as ITSIM (Indian Traffic Simulation Model). Graphic display program system constitutes three modules. They are ANIMATE, TSD and FSD. Animate modules animate traffic flow on roads. TSD module displays time space diagram and FSD module displays flow status diagram.

2.8 SUMMARY

In the present chapter review of most of the models simulating homogeneous and heterogeneous traffic on roads have been donc. Detailed descriptions of some of the models for mixed traffic simulation have been given, which further enhance the understanding of modelling aspect involved in heterogeneous traffic flow situation.

Chapter 3

MODELLING OF MIXED TRAFFIC FLOW ON URBAN ROADS

3.1 OVERVIEW OF SIMULATION MODEL SYSTEM

The formulated Traffic Simulation System consists of various component submodels which are assembled into a realistic structure of the system. The various submodels, the activities associated with them and their linkages are shown in Figure 3.1.

The heart of the system is the development of traffic simulation model, which simulates the flow of vehicles. Road and traffic submodels are developed to generate the road and traffic input respectively for the simulation model. To understand the working of the simulation model, animation programme system is developed to have the graphic display of the simulated traffic. The model output is analysed through traffic results processing programme to get the statistics of different performance measures. Some parameters of traffic flow are estimated through analysis of the field traffic data. Calibration of model parameters and decision thresholds is attempted by estimated traffic flow parameters and also through simulation experiments. The simulation model is validated for a number of measures of effectiveness (MOE). The validated simulation model is used to conduct a series of simulation runs to judge the sensitivity of some road and traffic characteristics.

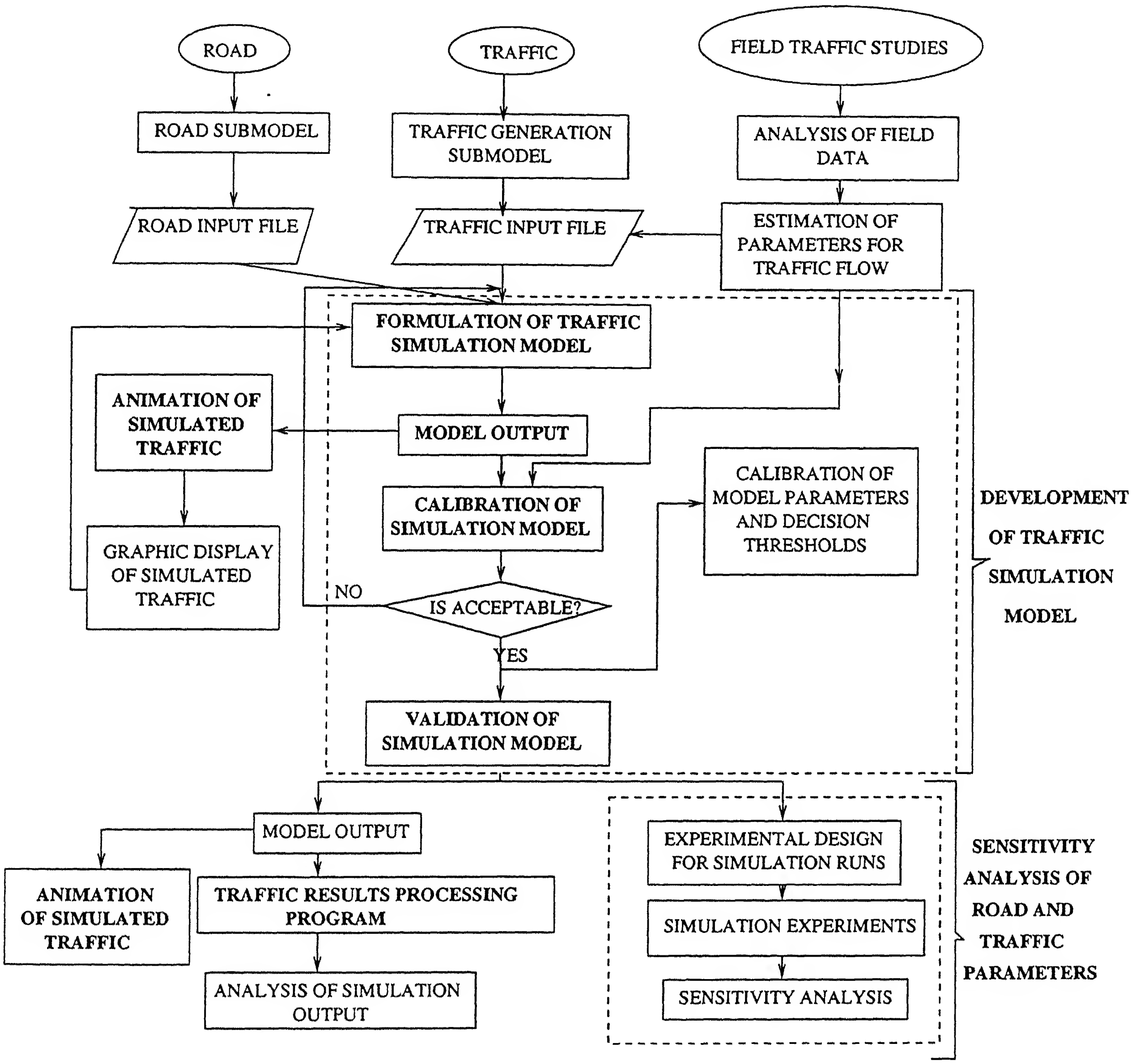


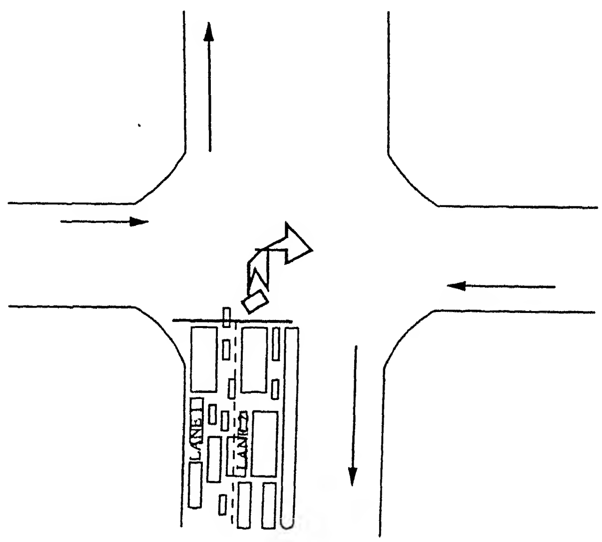
Figure 3.1: Overview of Traffic Simulation Model System

3.2 COMPLEXITIES OF HETEROGENEOUS TRAFFIC

On urban roads in developed countries, motorised vehicles like cars, trucks, buses etc., constitute over 90 percent of the traffic and the mix is considered to be homogeneous. For other situations, traffic is considered to be heterogeneous. Traffic on urban arterials in India are highly heterogeneous due to mix of different types of motorised and non-motorised vehicles.

3.2.1 Lane Configurations and Lane Discipline

In heterogeneous traffic mix, there is no lane discipline adopted by vehicle. On a two lane (7 metre) wide road, vehicles move in more than two queues, for example, 7-8 bicycles can move parallel. An example of lane occupancy in heterogeneous traffic is shown in Figure 3.2. It is observed that there are more than one vehicle in a lane. It can also be seen that there is no definite lane pattern and road occupancy depends upon available free road space, lateral space required by vehicles on both sides, and vehicle dimensions. Turning movement of vehicles at an intersection are also shown. There is no definite queueing pattern at the intersection and number of queues is dependent upon vehicle dimensions and lateral space required by the vehicles.

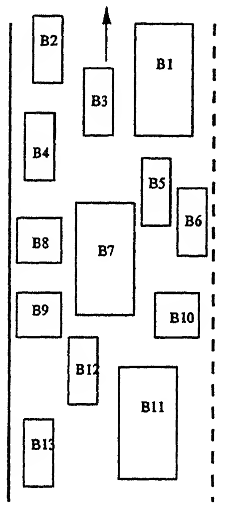


Movement of Heterogeneous Traffic

Figure 3.2: Lane Concept and Lane Discipline in Heterogeneous Traffic

3.2.2 Free Flow

In heterogeneous traffic, a vehicle at an instant follows more than one vehicle depending upon the type and number of vehicles ahead of it. For free flow case, required lateral width is the sum of the width of the vehicle and the lateral spacing required to maintain free flow. A vehicle is said to be free flowing, if (a) there is sufficient space and time headway with respect to vehicles ahead and (b) all the affected vehicles ahead are having relatively higher speed. As illustrated in the Figure 3.3, vehicle B11 is following vehicles B7 and B10. To test whether vehicle B11 is free flowing or not, it will compare its speed both with vehicle B7 and B10 and also whether it will get adequate spacing with respect to vehicles B7 and B10.



HETEROGENEOUS
Parallel / staggerd entity following

Figure 3.3: Constrained Flow in Heterogeneous Traffic

3.2.3 Constrained Flow

In the heterogeneous traffic, a vehicle may be constrained by more than one vehicle at an instant. Therefore, acceleration capability of a vehicle depends upon the speed and acceleration of the nearest vehicles. Vehicle B11 may be following vehicles B7 and B10. It is also seen that both vehicles B5 and B6 follow same vehicle B1. Thus in heterogeneous traffic, one vehicle can constrain more than one vehicle and a vehicle may follow more than one vehicle at a time.

3.2.4 Lane Changing

In heterogeneous traffic, though there is no specific lane concept, yet overtaking and yielding manoeuvers take place. Vehicles try to maximize road usage by a complex set of actions in which it is difficult to distinguish between passing, accelerative/flying overtaking or some combination of these. If a vehicle desires to overtake a slow moving vehicle in front, then the latter shifts to the left depending upon the space available and the space required by the overtaking vehicle. If this left shift of the slow moving vehicle clears the way, the faster vehicle will perform the overtaking operation without shifting to right. This type of overtaking is defined as passing. However, if left shift of the slow moving vehicle is not sufficient, then rear vehicle attempts to shift to the right for performing safe overtaking operation. This maneouver is defined as overtaking operation. Lane changing pattern followed in heterogeneous traffic flow situation is illustrated in Figure 3.4. Where vehicle A4 wants to overtake vehicle A3, by shifting to the right. For shifting to the right, vehicle A4 should ensure that free road space is adequate between vehicles A5 and A2. If time and space gaps are appropriate, then A4 will perform right shifting operation.

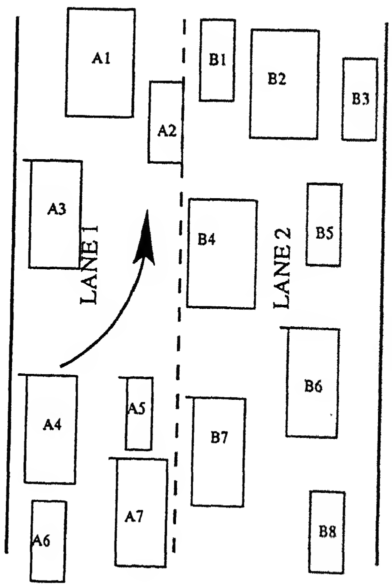


Figure 3.4: Lane Changing and Overtaking in Heterogeneous Traffic

3.3 VEHICLE CLASSIFICATION FOR HETEROGENEOUS TRAFFIC

In heterogeneous traffic, vehicles have wide variation in dimensions, operating speed, acceleration/deceleration capability, power-mass ratio etc. Study indicates that about 20 vehicle types use the same roadway. These vehicles range from fast moving car to slow moving push cart, and are present in different proportions. Some of the vehicles like cars, jeeps etc. though have some variations in their characteristics, but generally observe same type of flow logic on urban roads. Same way trucks, buses and other heavy vehicles follow similar type of flow logic. Therefore, different types of vehicles are aggregated into eight groups depending upon close resemblance in terms of physical and operational characteristics. Type of vehicles, their characteristics and group classification adopted for simulation are presented in Table 3.1.

3.4 ROAD SUBMODEL

Aim of the road submodel is to represent the road system so as to closely study the interaction between the vehicles and the road. This representation is done both in lateral and longitudinal directions. Lateral representation is generally expressed in terms of the number of lanes as motorised vehicles occupy full lane width. The longitudinal geometrics vary from location to location. Longitudinal representation can be expressed in terms of curvature, sight distance, and speed limitation. In most of the simulation models, road system is divided into homogeneous road blocks and homogeneity is with reference to various road characteristics.

3.4.1 Representation of the Road System

Representation of road, in most of the earlier simulation models, involves lane definitions. Road stretch consist of homogeneous blocks. Successive road blocks are an ordered list. Singly or a doubly linked lists have been used for representing adjacent road blocks. If a road stretch contains n lanes then it will require n lists to represent such a road in the computer model. Representation of a two lane road by a doubly linked list is shown in Figure 3.5. When a vehicle enters or leaves a particular lane, *insert vehicle* or *remove vehicle* operations are performed respectively on the linked list representing the lane. Figure 3.5 illustrates the manner in which vehicle pointers of doubly linked lists are used by vehicles for lane changing. It can be seen that the lane 1 has A1, A2, ..., and A7 and lane 2 has

B1, B2, ..., and B7 vehicles. Suppose A3 wants to change from lane 1 to lane 2. For lane changing (merging), vehicle A3 look for time and space gap between vehicles B2 and B3. On a two lane road system lane changing operations can be performed in the following manner.

Table 3.1: Vehicle Types Considered in Simulation Model

Group	Type of Vehicles	Width	Length
Group I	**Car Group**		
	Maruti Van	1.40	3.15
	Maruti Car	1.40	3.20
	Fiat	1.45	3.90
	Ambassador	1.60	4.15
	Jeep Mahindra	1.55	3.70
	Jeep Gypsy	1.45	3.90
Group II	**Motorised Three Wheeler Group**		
	Tempo	1.60	3.25
	Auto Rickshaw	1.20	2.40
Group III	**Light Commercial Vehicle Group**		
	Mini Bus	1.80	4.83
Group IV	**Heavy Motorised Vehicle Group**		
	Bus (Large)	2.30	7.60
	Truck Tata	2.35	6.80
	Truck Tata Large or Ashok Leyland	2.35	7.20
Group V	**Motorised Two Wheeler Group**		
	Scooter	0.60	1.70
	Motor Cycle	0.70	1.90
Group VI	**Large NMV Group**		
	Push Cart (Small)	1.00	1.60
	Push Cart (Large)	1.50	4.15
	Buffalo Cart	1.80	7.50
	Horse Cart	1.30	4.10
Group VII	**Bicycle Group**		
	Bicycle	0.45	1.70
Group VIII	**Cycle Rickshaw Group**		
	Cycle Rickshaw	0.95	2.65

A3 changing from its present lane 1 to lane 2 *Delete vehicle* operation will be performed on doubly link list representing lane 1 (deleting vehicle pointer node A3) and

add vehicle operation will be performed on doubly link list representing lane 2 (adding vehicle pointer node A3 in between vehicle pointer nodes B2 and B3).

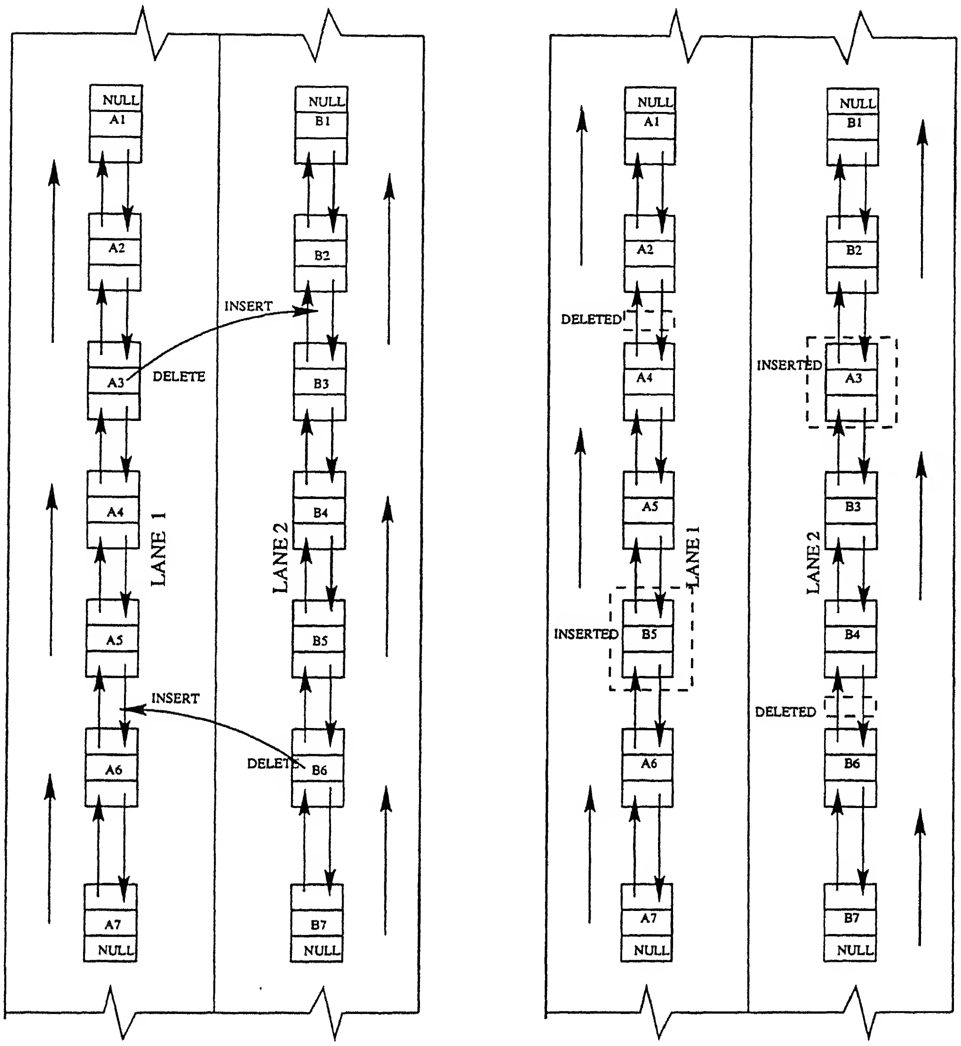


Figure 3.5: Representation of a Two Lane Road by Doubly Link Lists and Changing of Lanes by Performing Add and Delete Operations

Representation of road in homogeneous traffic model is simple. Overtaking, yielding and passing operations can be represented with the help of add vehicle and delete vehicle operations. Hence the space concept is implicit in lane definitions and if a vehicle wants to change its position laterally it has to move from one lane to another. It means that minimum

lateral movement of a vehicle is the width of the lane. However, the model is not capable of giving exact lateral space coordinates during simulation.

Road has also been represented by strips in which lateral movement of the vehicles is represented by width of the strips (Sutomo, H., 1992; Hoqe, S., 1994). Width of a strip can be varied as per the requirements of lateral movement. The road representation by strips as used in TRASMIC model is shown in Figure 3.6.

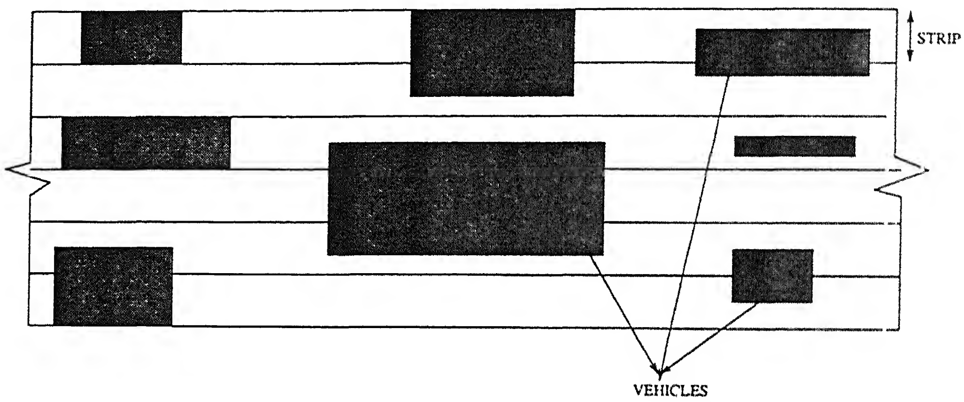


Figure 3.6: Road Representation by Strips (TRASMIC)

For complex heterogeneous traffic the lateral representation in terms of lane/strip is not appropriate as vehicles have wide variations with reference to width. Narrow vehicles like bicycles, scooters etc. can occupy just a portion of lane, two or more of them can move parallel in a lane.

To realistically represent the road system for mixed traffic, it is proposed to divide the road into narrow strips. The width of a strip depends upon dimensions of various vehicle types. The longitudinal representation can be done by homogeneity of the road characteristics. But within a homogeneous road block, the road is further divided into smaller units of length to process the complex heterogeneous traffic. In this manner the road is being represented by a grid pattern. This representation has the capability to quantify exact lateral displacement by a vehicle and also facilitates modelling various traffic interactions and their action patterns. A grid of one metre square is adopted and upto four vehicles can share this area. The model has the flexibility of changing grid size and vehicle occupancy.

The effect of the vertical gradient is considered for calculating acceleration and deceleration capability of the vehicle by using force equation (equation 3.8). Likewise speed limit factor is also incorporated in this model. As grid is of small size, there will be no abrupt

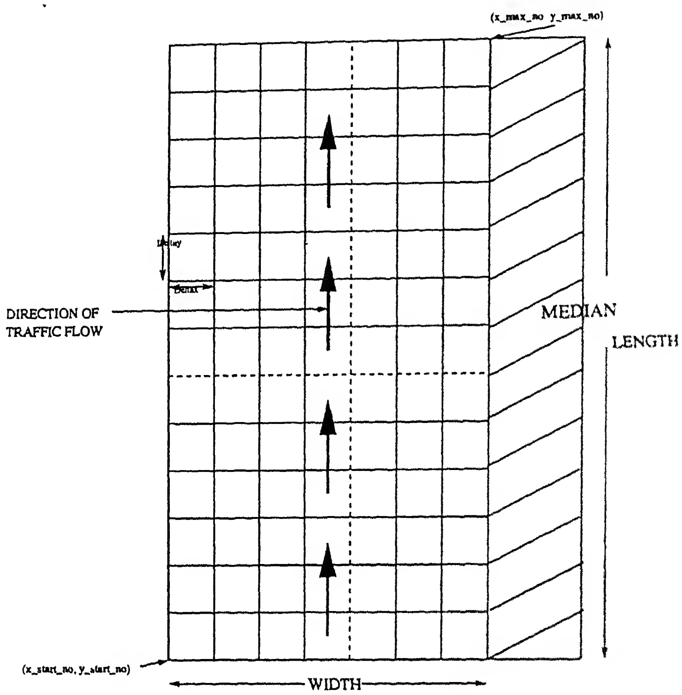


Figure 3.7: Grid Representation of Road in Road Generation Sub-Model

3.5 VEHICLE DATA STRUCTURE

Vehicle is defined as an object, consisting of static and dynamic variables.

STATIC VARIABLES: Static variables are input to the simulation model and are generated stochastically by assumed distributions. These are:

- Vehicle Type and identification number
- Entry time
- Entry lateral and longitudinal coordinates
- Exit lateral and longitudinal coordinates
- Entry and free speeds
- Maximum acceleration and deceleration capability
- Power weight ratio

DYNAMIC VARIABLES: Dynamic variables change with time and their values depend upon logical decisions taken by the vehicle. Dynamic variables describe the position, motion attributes, and flow status at different times. Some of the dynamic variables are used for obtaining output of the simulation model. The output of the models are concerned with the flow characteristics along the road section, and system performance measures of individual vehicles. Output also includes the statistical distributions of different parameters, which helps in calibration, validation and in testing sensitivity of the model. The following dynamic variables are considered for defining vehicle.

- Vehicle time, position and motion attributes
  - Current simulation time
  - Lateral and longitudinal positions of the vehicle at current time
  - Speed and acceleration of vehicles at current and previous time intervals
  - Lateral space required by the vehicle
- Free and constrained status variables
  - Flag indicating that the vehicle is free
  - Flag indicating that the vehicle is constrained
  - Type and identification number of the vehicle by which current vehicle is constrained
- Overtaking status variables
  - Flag for overtaking on the right
  - Type and identification number of the vehicle which is overtaken on the right
  - Required right shift in lateral direction to perform overtaking on the right
  - Flag for overtaking on the left
  - Type and identification number of the vehicle which is overtaken on the left
  - Required left shift in lateral direction to perform overtaking on the left
- Yielding status variables
  - Flag for yielding
  - Type and identification number of the vehicle for which current vehicle is yielding
  - Required left shift in lateral direction to give space for overtaking vehicle

Apart from the above mentioned vehicle attributes, some other parameters and distributions are required to make logical decisions for some of the traffic operations performed by the vehicle. However, value of these parameters and distributions is common for the vehicles of a certain group. Therefore, these parameters are not used as variable in the vehicle data structure, and this helps in curtailing computer memory requirement. Such type of parameters and distributions are read for different vehicle groups.

3.6 TRAFFIC GENERATION SUBMODEL

Aim of this model is to generate the traffic input to the simulation model. Traffic input includes all parameters of the vehicle to be simulated on a road stretch. These parameters are identity number, free speed, vehicle type and other attributes (entry time, lateral and longitudinal coordinates at entry). These parameters may be directly observed from the field data or generated using specific distribution.

Two different models have been proposed for traffic generation. The first model directly usesfield data for traffic generation while the second model attempts to generate generalised traffic in which the attributes are randomised.

3.6.1 Pseudorandom Number Generator

Uniformly distributed random number play an important role in the generation of random variables drawn from other probability distributions. The numbers generated by computer subroutines are called pseudorandom numbers.

An ideal pseudorandom number generator generates a sequence of numbers that are uniformly distributed; statistically independent; reproducible; and nonrepeating for any desired length. In the present work multiplicative congruential method is used and it is as follows

$$I_{j+1} = aI_j mod(m) \tag{3.1}$$

where I_j, I_{j+1} are integers.

Park and Miller (1988) have surveyed a large number of pseudorandom number generators that have been used over the last 30 years. Along with a good theoretical review, they present on anecodtal sampling of a number of inadequate generators that have been used. There are good evidences, both theoretical and empirical, that the simple multiplicative algorithm can be as good as any of the more general linear congruential generator if the multiplier a and modulus m are chosen carefully. Park and Miller (1988) proposed a choice

of multiplier and modulus as $a = 7^5$, and $m = 2^{31} - 1$.

3.6.2 Random Numbers with Specified Distribution

Generation of random variables of different distributions can be derived from uniformly distributed random variables. Let the cumulative probability function $F(x)$, of a stochastic process be

$$F(X) = Prob[x <= X] = f(t)dt \tag{3.2}$$

where $F(X)$ is defined over the range $0 \leq F(X) \leq 1$ and $f(t)$ represents the probability density function of random variable X at $X = t$.

As $F(X)$ has a uniform distribution over $(0 - 1)$ range, uniformly distributed random numbers r in the $(0 - 1)$ range are generated and set $F(X) = r$. For any particular value of r (say r_0), which is generated, it is possible to find the value of X (in this case X_0) corresponding to r_0 by the inverse function.

$$X_0 = F^{-1}(r_0) \tag{3.3}$$

where $F^{-1}(r_0)$ is the inverse transformation of r on the unit interval into domain of X.

3.6.3 Generating Normal Distribution

From the free speed study it was found that free speeds of a particular vehicle type follow a normal distribution with the range of $(\mu - 3\sigma)$ to $(\mu + 3\sigma)$. Some of the researchers have used central limit theorem to find (R) for normally distributed random variables by taking the sum of twelve uniform variables, that can be given by following expression
$R = \Sigma(r_i - 6.0)$

In the present study, Box and Muller (Ravindran et al., 1987) technique has been used for generation of standard normal variables.
The expressions used are:

$$x_1 = [-2\log(R_1)]^{1/2}\cos(2\pi R_2) \tag{3.4}$$

$$x_2 = [-2\log(R_1)]^{1/2}\sin(2\pi R_2) \tag{3.5}$$

where R_1 and R_2 are two uniform random fractions.

Knowing the normally distributed random variable R from the above expression, the free speed of vehicle (v_{fr}) of category k can be determined by using R, μ_k and σ_k.

$$v_{fr} = \mu_k + R\sigma_k \tag{3.6}$$

where μ_k and σ_k are the mean and standard deviation of free speeds for k type vehicle.

3.6.4 Traffic Generation from Field Data

It may be necessary to simulate the observed traffic on a road to calibrate and validate the simulation model. The following data may be collected from the field:

a Identity number

b Vehicle type

c Direction of travel

d Longitudinal and lateral coordinates at entry

e Entry speed

f Entry time at the section

Free Speed Free speed distributions are calibrated for different vehicle types and are normally distributed. Free speed is generated by normal distribution and it is ensured that free speed would not be less than entry speed.

$$v_{fr} > v_{ent} \tag{3.7}$$

where v_{fr} = free speed;
v_{ent} = entrance speed.

p-value (Power Mass Ratio)

The p-value is randomised from the power mass ratio distributions. A check is then made to ensure that p-value is sufficient enough for the vehicle to be able to maintain its free speed v_{fr} on a level road (zero gradient).

The equation of motion (force equation) for a vehicle is described as

$$\frac{dv}{dt} = \frac{p}{v} - \frac{C_a A}{m}v^2 - (C_{r1} + C_{r2}v) - gi \tag{3.8}$$

where $\frac{dv}{dt}$	=	acceleration capability of vehicle in m/sec^2;
m	=	vehicle mass in kg;
g	=	gravitational acceleration in m/sec^2;
i	=	gradient;
p	=	power mass ratio;
C_a	=	air resistance coefficient in kg/m^3;
A	=	Frontal area in m^2;
C_{r1}, C_{r2}	=	Rolling resistance coefficient; and
v	=	vehicle speed in m/sec

If $\frac{dv}{dt} = 0$ and $i = 0$, the following equation is derived from the above equation for the equilibrium speed v_e on a level road for a vehicle with p-value p.

$$\frac{C_1 A}{m} v_e^3 + C_{r1} v_e + C_{r2} v_e^2 - p = 0 \tag{3.9}$$

By using numerical techniques, the above equation is solved to obtain equilibrium speed. If v_e is greater than or equal to v_{fr}, the p-value is sufficient enough to maintain its free speed. Else, a new p-value is randomised from assumed power mass ratio distribution for given vehicle type until a large p-value is obtained for maintaining the vehicle free speed on a level road.

3.6.5 Generating Randomised Traffic

For randomised traffic, different distributions are considered for generating vehicle and traffic characteristics. The generated traffic attributes are as explained in the field traffic generation, but methods of obtaining these parameters are different in some cases.
Identity Number: An identity number is assigned for each vehicle to be simulated.

Vehicle Type: Vehicles have been classified into twenty types. When a vehicle enters the road section, it is necessary to know its type in order to assign the attributes like entry space, free speed, entry speed, power-mass ratio etc. It is possible to specify for any category of vehicle a subrange corresponding to composition in the overall range of (0-1) for $F(x)$.

Longitudinal Coordinates at Entry and Exit: These are fixed based on section to be simulated.

Lateral Coordinates at Entry and Exit Lateral coordinates are generated from calibrated cumulative entry space distributions for different types of vehicles.

Entry Time: The inter arrival time gaps between the vehicles have been found to follow Schuhl's and modified-Schuhl's headway model. In the present study these models have been considered for generating traffic. In the Schuhl composite headway model, probability p of a gap being less than t seconds is given by

$$p(h < t) = (1-\alpha)[1 - exp(\frac{-t}{T_1})] + \alpha[1 - exp(-\frac{t-\tau}{T_2 - \tau})] \qquad for\ t \geq \tau \tag{3.10}$$

where h = time headway in seconds,
α = fraction of total flow made up of constrained vehicles,
T_1 = average headway of free flowing vehicles in seconds,
T_2 = average headway of constrained vehicles in seconds,
τ = shift of curve (i.e. minimum headway) for constrained vehicles in seconds, and

Similarly in the modified-schuhl composite headway model, probability p of a gap being less than t seconds is given by

$$\begin{aligned}(p(h < t)\prime = \; & (\alpha_{un})[1 - exp(\frac{-t}{T_{n1}})] + \alpha_{cn}[1 - exp(-\frac{t-\tau_n}{T_{n2} - \tau_n}] \\ & (\alpha_{um})[1 - exp(\frac{-t}{T_{m1}})] + \alpha_{cm}[1 - exp(-\frac{t-\tau_m}{T_{m2} - \tau_m})] \\ & for\ t \geq \tau_m, t \geq \tau_n\end{aligned} \tag{3.11}$$

where α_{cn} = fraction of total flow made up of constrained NMV's,
α_{cm} = fraction of total flow made up of constrained MV's,
α_{un} = fraction of total flow made up of unconstrained NMV's,
α_{um} = fraction of total flow made up of unconstrained MV's,
T_{n1} = average headway of free flowing NMV's in seconds,
T_{m1} = average headway of free flowing MV's in seconds,
T_{n2} = average headway of constrained NMV's in seconds,
T_{m2} = average headway of constrained MV's in seconds,
τ_n = shift of curve (i.e. minimum headway) for constrained NMV's in seconds,
τ_m = shift of curve (i.e. minimum headway) for constrained MV's in seconds, and
V = total number of vehicles arriving during time T.

By using Newton Raphson technique, inter arrival gap by Schuhl and Modified-Schuhl distributions can be computed (for the given probability p). From the sequence of arrival gap lengths t_i, the arrival time of ith vehicle is computed as:

$$Arr\_t_i = Arr\_t_{i-1} + t_i \tag{3.12}$$

where Arr_t_i = Arrival time of i-th vehicle;
Arr_t_{i-1} = Arrival time of $(i-1)$-th vehicle;
t_i = Inter arrival time gap between ith and (i-1)th vehicle.

Free Speed: Free speed is generated as described in case of traffic generation for field traffic.

Entry Speed: Entry speed depends upon the road characteristics of the entry block, traffic position and status in close vicinity, traffic composition, flow rate, and traffic density of the road section. This is some fraction of vehicle free speed and can be obtained by adjusting free speed of vehicle with a coefficient, which is always less than unity. Under free flow condition value of coefficient is higher and decreases under high flow level condition and needs to be calibrated. When entry speed is being generated from the field data direct value may be obtained. Under conditions when it is not possible to directly obtain the entry speed, an additional warming up road section may be considered before the simulated road stretch.

p-value: Power-mass ratio is also generated as described in case of traffic generation for field traffic.

3.6.6 Macro Algorithm for Traffic Generation Submodel

Procedural steps involved in traffic generation submodel are shown in Figure 3.8.

3.7 SCANNING TECHNIQUES

Traffic simulation process is to move the vehicles over the road and update the vehicle characteristics like lateral and longitudinal positions, speed, type of flow status - constrained, free, overtaking, yielding etc. at different times. Traffic flow process requires continuous scanning along time and road space in order to predict the position and other vehicle characteristics at different times. As continuous scanning of time and road space is not feasible in digital simulation, so time and road space are discretized. The road space is divided into grids of width Δx and length Δy.

Scanning of the simulation process can be accomplished in two ways; (i) Periodic scanning or fixed time scanning method; and (ii) event oriented scanning or variable time increment method. In the periodic scan method, scanning and updating of the traffic system (i.e., move vehicles, change their speeds, coordinates, etc.) is done periodically; that is, scan the model once every t sec. In the event scan method, when even a specific event occurs, it is included in event list. The status of a system is updated by events present in event list. Scanning is done to determine when the immediate next event occurs and the system is updated. The procedure is repeated throughout simulation time.

Event oriented scanning is computationally efficient but involves greater programming complexity. Traffic flow for heterogeneous traffic involves a larger number of events to be

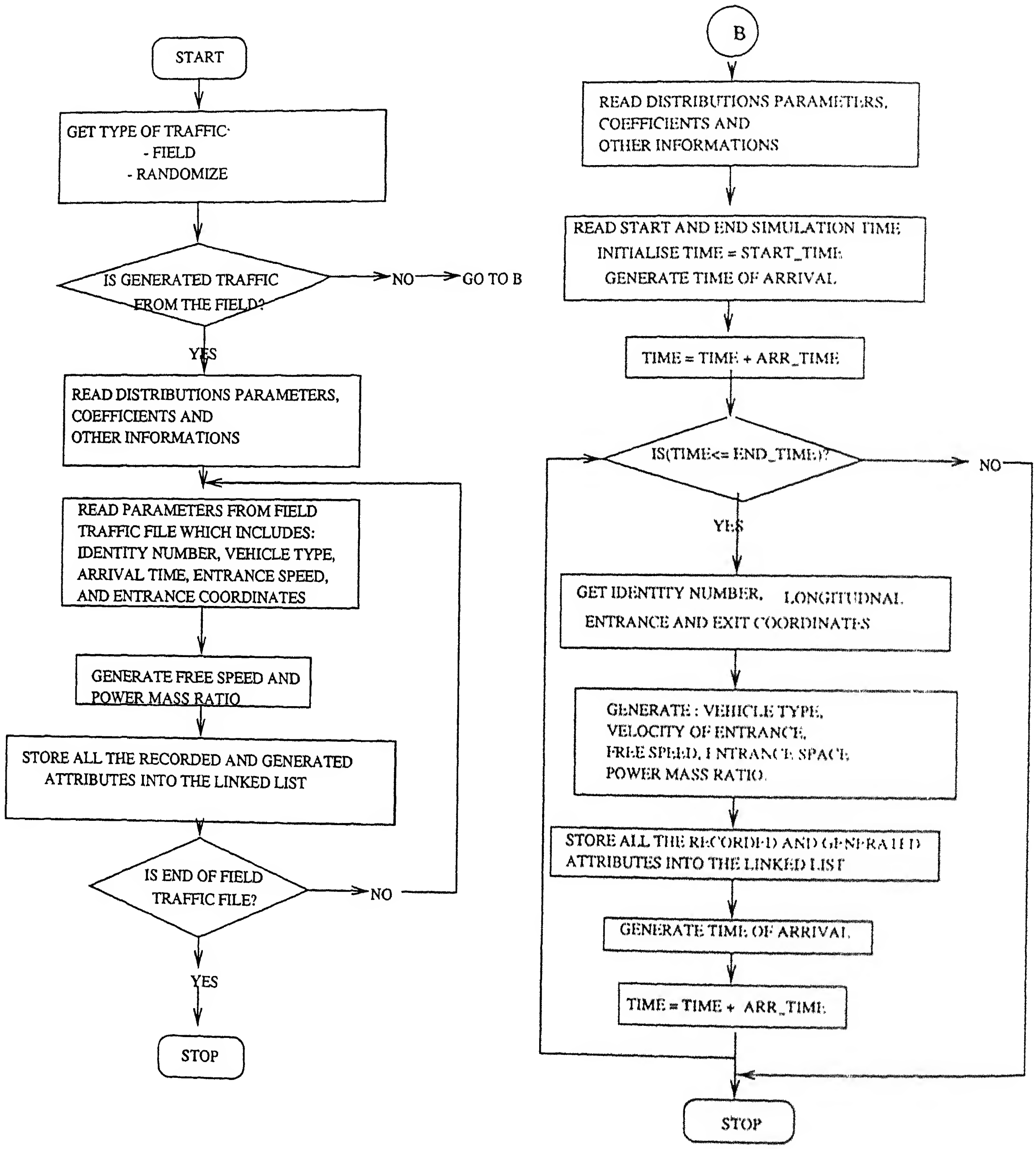


Figure 3.8: Flow Chart for Traffic Generation Submodel

scanned. To keep track of all these events by event oriented scanning is extremely difficult, though not impossible. The set of probable events that can occur is large and the events occur at close time intervals. In such a situation periodic scanning is easy to formulate and is adopted in this study. Periodic scanning technique has extra advantage of compatibility with physical representation of computer model, which has been used along with vehicle pointer referencing system. For simulation runs performed in this study a time interval of one second is adopted. This time interval can also be changed as desired.

3.8 REPRESENTATION OF THE FLOW SYSTEM

In general there are two ways of representing and manipulating discrete objects such as vehicles with the aid of a digital computer: (1) physical representation and (2) memorandum representation.

In the memorandum representation, the characteristics of the vehicles like location, speed, length, group number(category of the vehicle) etc. can be stored by using a coded word or group of coded words. In each scanned time interval, data are updated and the information concerning the vehicle characteristics is changed, when required.

In physical representation, the memory locations are associated with the blocks in physical space. The information in the memory location contains the information concerning presence or absence of the vehicle in the given road block and their characteristics. The data in the memory location is scanned to identify the characteristics of the traffic and are updated at every time interval.

For a 7 m wide road of one km length, there are 7000 grid elements of size (1m $\times$ 1m) to represent the road system. Due to number of vehicle attributes, memory requirement is very large in such type of representations. Hence pointer referencing system has been used, which curtails memory requirement and facilitates data manipulation and management. In the pointer referencing system, vehicle attributes are stored at specified locations and are accessed through pointers by passing the addresses of these storage locations.

3.9 TRAFFIC INTERACTION MODEL

This model involves the study of various interactions among the vehicles and the operations related to different types of interactions. This is the heart of traffic simulation model and involves complex decision processes.

A vehicle moving on the road section may be free flowing, following, yielding, overtak-

ing/passing at different time intervals. These types of flow logics involve changes in speed, lateral and longitudinal movement along the road. In the dynamic traffic simulation system, the decision making for these type of flow logics needs to be realistically modelled. The model has identified different types of flow logics. For each flow logic the strategy for decision making is evolved. Far a particular decision the operations to be performed like speed change, lane change etc. are determined and the flow system is updated. At any instant of time the vehicle may be operating in one of the identified flow logics.

3.9.1 Flow Logic of Vehicles

In the present study, three broad categories of flow status of vehicles are considered. For convenience in micro-level analysis, various movement types in each flow status are termed as 'mode'. Different flow status and the eleven different modes included in them are as follows.

- Free Flowing
  - Free Flowing
- Constrained Flowing
  - Following Started
  - Following Continued
  - Following Terminated
  - Stopped
- Overtaking and Yielding
  - Accelerative/Flying Overtaking Started
  - Accelerative/Flying Overtaking Completed
  - Passing Started
  - Passing Completed
  - Yielding Started
  - Yielding Completed

Figure 3.9 shows the different flow status of vehicles. In the portion OA, vehicle is moving in free flowing mode. At the point A (decision point - interaction started), vehicle starts interacting with a slower vehicle ahead. At this point of time vehicle will search for possibility to overtake without reducing its speed. In the portion AB vehicle will try to perform flying overtaking (overtaking without reducing its speed). At the point B (decision point -

following started) vehicle finds that available space and time headway are not adequate to overtake vehicle ahead. At the point B vehicle will start following slower vehicle ahead. In order to maintain adequate space headway, vehicle decelerates its speed up to point C. After point C (decision point - following continued) vehicle enters into following continued mode. In the portion CD vehicle looks for overtaking opportunity at regular time intervals. In the portion BC vehicle adopts car following strategy to calculate its deceleration rate in terms of its relationship with the leading vehicle. In the present study linear type of car following model has been used. Certain checks are also made on the acceleration rate obtained from the car following model to ensure that acceleration rate falls within the permissible range.

Similarly in the region BC vehicle can also calculate its deceleration rate by using space headway polynomials obtained from the field studies. Space headway polynomials are used for getting required space headway in constrained flow situations. In this case also checks are applied on the acceleration rate as in the car following model. In portion CD, vehicle looks for appropriate time and space gap for overtaking slow moving lead vehicle. When gap is adequate, vehicle decides to overtake. It is referred as point D (decision point following terminated or overtaking started). In portion DE vehicle accelerates to perform safe overtaking operation (accelerative overtaking). As shown in Figure 3.9 overtaking operation is completed at E and vehicle again returns to free flowing state.

3.9.2 Strategy for Decision Making of Flow Logics

The formulated flow logics involve large number of decision points. In the complex mixed traffic flow, a vehicle may be interacting with other vehicles in front, rear and side. Based on the locations, speeds, times and caught up vehicles in its vicinity, an appropriate flow logic is to be determined. Once a decision is made then the vehicle will perform the relevant operation of that logic and the location, speed, status of the vehicle are updated at regular intervals.

The overall strategy of the traffic interaction mode for the vehicle operates as follows:

- Check the status of the vehicle. Depending upon the status of the vehicle, identify the flow logic.
- Check positioning of the vehicle with reference to physical boundaries. Decision depending upon status variables may be modified if required.
- A certain area on all sides of the vehicle is searched and the status of the vehicles in those areas are identified. The area search in lateral and longitudinal directions should be in consistence with the various flow logics of the vehicles.

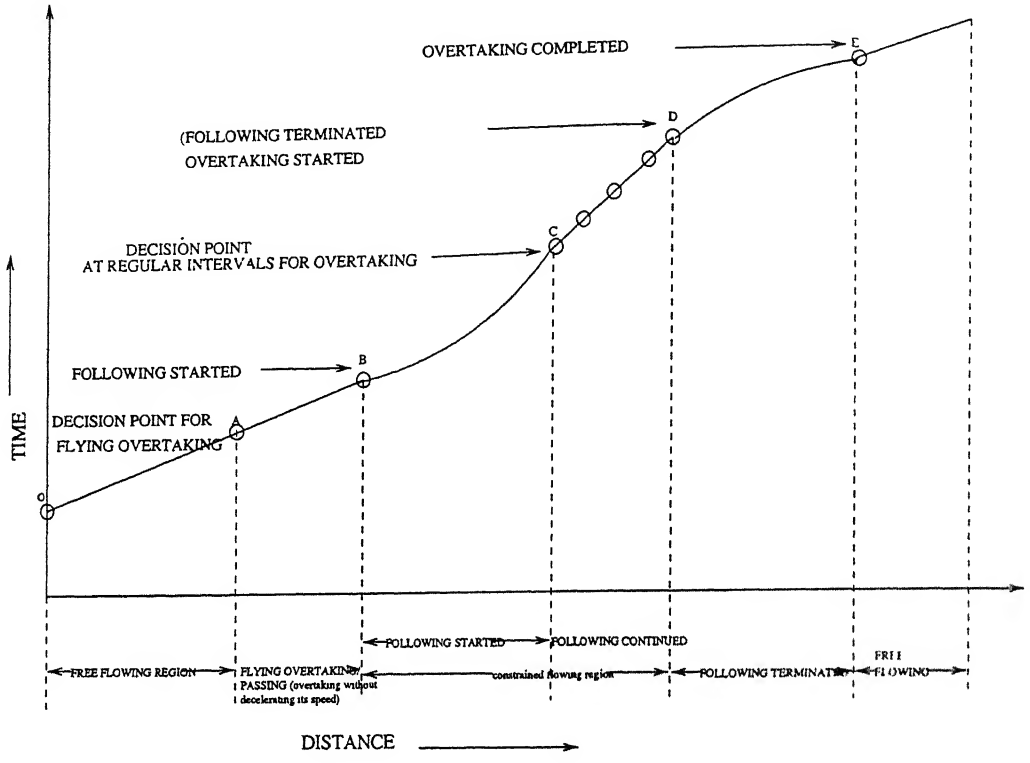


Figure 3.9: Flow Status of Vehicles

- Do sorting of the vehicles in the search area, and select the interacting vehicles.
- Obtain attributes required for describing selected traffic flow operation. Attributes are calculated by studying various conditions between current vehicle and interacting vehicles.
- Update the dynamic variables of the vehicle structure and assign vehicle to new position.

3.9.3 Longitudinal Spacing

When a vehicle is following, it maintains a certain spacing with respect to the front vehicle as shown in the Figure 3.10, vehicle B is following vehicle A. This spacing depends upon

the speed and length of the vehicle and a certain minimum time headway (t_h). A vehicle will maintain this minimum spacing with reference to the vehicle in rear. This spacing is designated as tail length of the vehicle. As no vehicle can come within this length, tail length can be expressed as longitudinal spacing from the front of the current vehicle to the front of the vehicle behind.

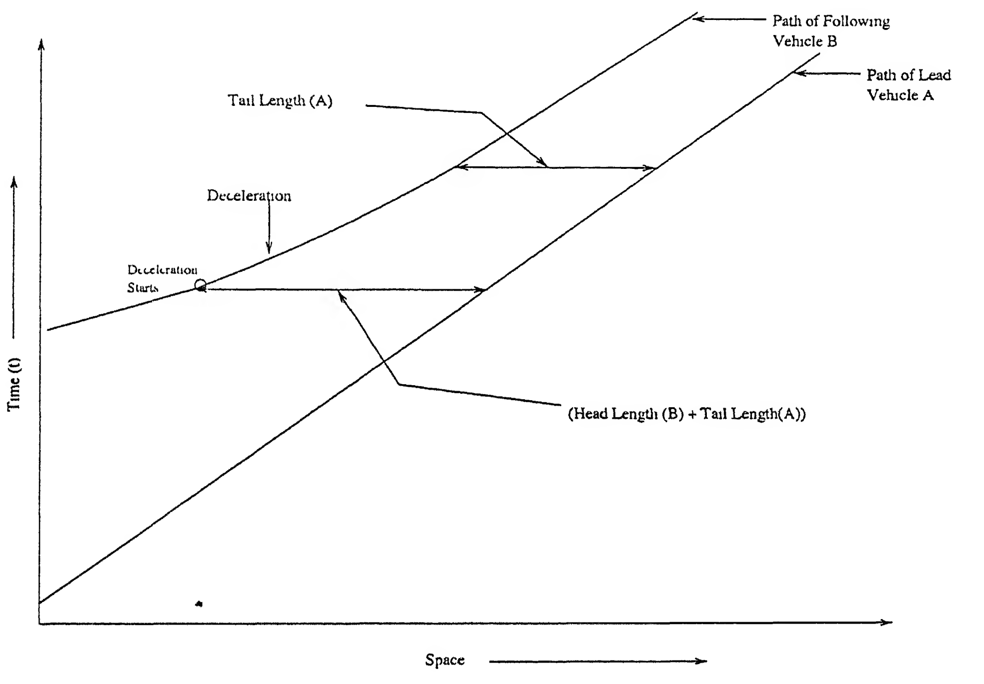


Figure 3.10: Time - Space Diagram of Lead and Following Vehicles

In the mixed traffic stream, there are wide variations in speed. Tail length as determined from minimum time headway may be very small for slower vehicle, may be even less than the actual length of the vehicle. To improve this relationship, a certain minimum spacing is specified as the lower bound for the tail length. In the present model tail length is defined as:

$$taillength_A = max(m_t, V_A * t_h) \tag{3.13}$$

where $taillength_A$ = tail length of vehicle A
V_A = speed of leading (front) vehicle
m_t = minimum tail length
t_h = minimum time headway

When a vehicle catches up slower vehicle ahead, it encounters the state where the decision

about the flying overtaking is to made, represented as decision point for flying overtaking. If the decision for flying overtaking is rejected then the vehicle decelerates till it attains the speed of the vehicle ahead ($V_B = V_A$). While following, the rear vehicle will maintain the longitudinal spacing of tail length. Distance traveled by the vehicle B in decelerating from the speed V_B to that of vehicle V_A is critical in the decision making process. This length depends upon the speed of the faster vehicle (V_B) and speed of the slower vehicle ahead (V_A) and deceleration rate of the vehicle. The distance traveled by vehicle B in reducing its speed from V_B to V_A is designated as head length of the vehicle. In the present model head length of vehicle B following vehicle A is defined as

$$headlength_B = \frac{V_B^2 - V_A^2}{2 * Dec}, \qquad for \;\; V_B > V_A \tag{3.14}$$

where $headlength_B$ = head length of vehicle B
V_A = speed of front vehicle
V_B = speed of following (rear) vehicle
Dec = maximum deceleration rate of vehicle

For head length and tail length of vehicle A and vehicle B reference can also made to Figure 3.11.

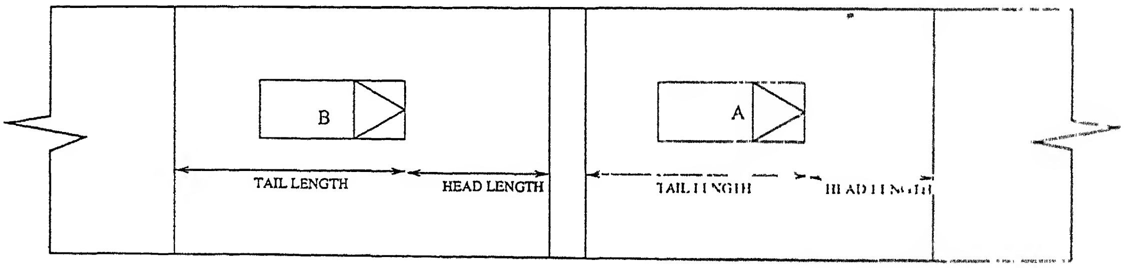


Figure 3.11: Representation of Vehicles as a Point, Head Length and Tail Length

In the present study, a constant deceleration rate, is assumed as 2.0 m/sec^2. Head length defined in equation ~~6.3~~ 3.14 ensures that distance is sufficient to avoid collision of following vehicle with the leading vehicle. Consider a critical case in which front vehicle comes to the standstill position. Let the distance moved by the following and lead vehicles before coming to the stand still position are l_1 and l_2 respectively. Distances l_1 and l_2 are also given below:

$$l_1 = \frac{V_B^2}{2 * Dec} \tag{3.15}$$

$$l_2 = \frac{V_A^2}{2 * Dec} \tag{3.16}$$

Therefore, required separation will be $l_1 - l_2$ given by

$$l_1 - l_2 = \frac{V_B^2}{2.0 * Dec} - \frac{V_A^2}{2.0 * Dec} \tag{3.17}$$

As $V_B > V_A$, this indicates that even in the critical case head length of vehicle B is adequate to avoid collision with vehicle A in front.

3.9.4 Inter-vehicular Lateral Spacing

Vehicles moving in a parallel stream try to maintain adequate lateral space from each other in order to avoid side swipe. Lateral space required by a vehicle is represented in Figure 3.12. Lateral space maintained by a vehicle is assumed as a function of minimum and maximum value of required lateral spacings, current speed, and minimum and maximum operating speeds of the vehicle.

$$\text{lateral space} = f(cu\_sp, min\_ls, max\_ls, min\_sp, max\_sp) \tag{3.18}$$

where cu_sp = current speed;
min_ls = minimum lateral spacing of a vehicle group;
max_ls = maximum lateral spacing of a vehicle group;
min_sp = minimum speed of a vehicle group; and
max_sp = maximum speed of a vehicle group.

The above function needs to be estimated from actual field observations.

3.9.5 Lateral Spacing from Fixed Objects

A vehicle attempts to maintain safe lateral clearance from the physical barriers such as median and road kerb etc. in order to attain safe speed and also to avoid collision. It is assumed that safe lateral spacing from the physical barrier is a function of vehicles speed (Figure 3.12).

$$ls\_fo = f(cu\_sp); \tag{3.19}$$

where ls_fo = lateral spacing required by the vehicle from the barriers.

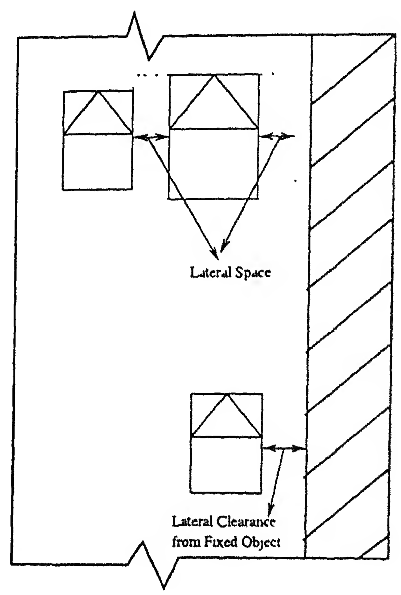


Figure 3.12: Lateral Space Required by Vehicles

3.9.6 Search Area

For decision making, area under the influence of a vehicle is to be scanned. To determine the flow logic of a vehicle at a certain instant, a certain area in the vicinity of the vehicle needs to be observed with reference to the vehicles present in that area and their flow status. The search has to be carried out in different directions as the vehicle may have to interact with the vehicles present in these directions. This model specifies a certain zone to be scanned and six types of search zones are identified. Each search area has a certain length in the longitudinal direction and a certain width. Three of these areas are in the front direction and three in the rear of the vehicle. These areas are given below.

- Ahead of the Vehicle
  - Frontal search area
  - Left frontal search area
  - Right frontal search area
- Rear of the Vehicle
  - Rear search area
  - Left rear search area

- Right rear search area

All these six types of search area as used in the model are given in Figure 3.13. Type of decisions to be taken and related movements for each of the search area are given in Table 3.2.

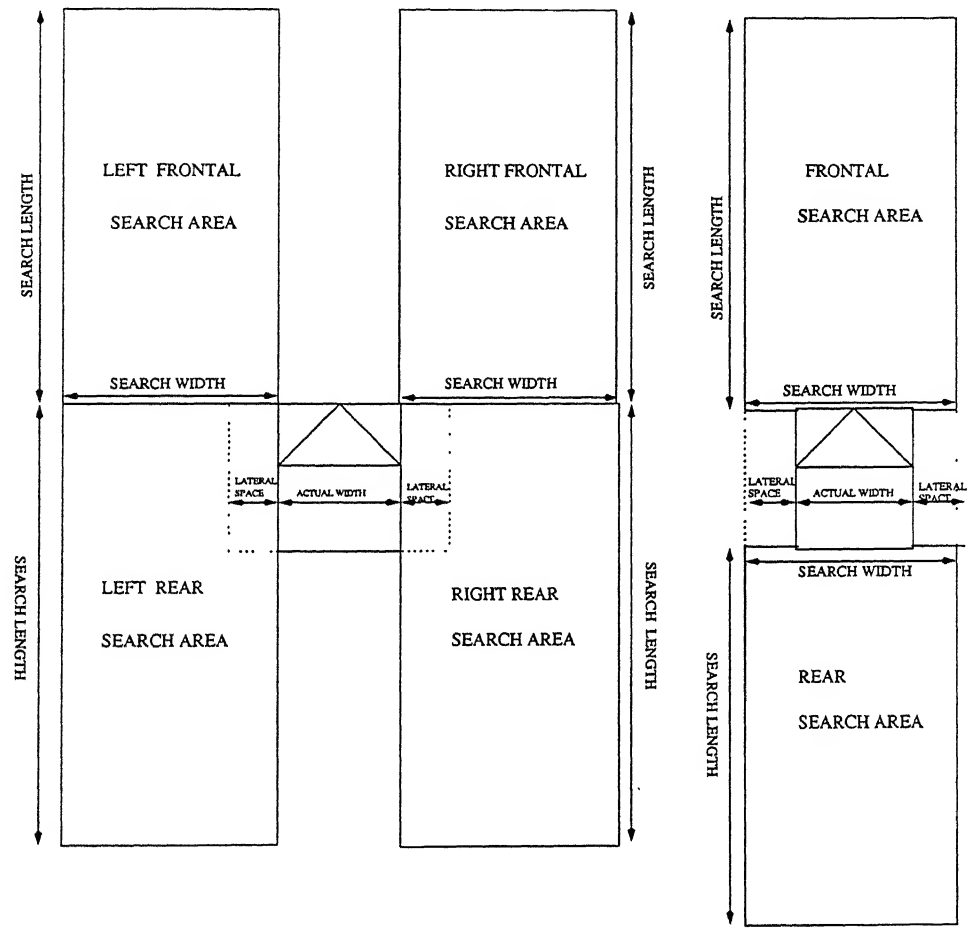


Figure 3.13: Different Search Areas

Proper choice of the length and width of search area is to be selected. If search area is small then there is a possibility of missing some interacting vehicles. If large value of search length and width are chosen, then it is expected that all vehicles which are interacting with the current vehicle will be considered in the decision process. But at the same time it increases computational effort as more number of grid elements are to be scanned and large memory requirement for storage of vehicle attributes. One can also choose a constant value

Table 3.2: Search Area

Type of search area	Decisions Involved and Vehicle Movements Calculated
Frontal search area	Overtaking decisions, checking free or constrained status, calculating forward movement
Left frontal search area	Left movement and forward movement
Left rear search area	Maximum possible left movement by considering left rear vehicles
Rear search area	Yielding decisions
Right frontal search area	Right movement and forward movement
Right rear search area	Maximum possible right movement by considering right rear vehicles

of influence length and width. Two methods have been considered for getting length and width of the search area. In the first method static search area is considered. It remains constant through out the simulation run and is not a function of current and interacting vehicles characteristics like speed, acceleration, free speed, power mass ratio etc. For this case large value of search length and width are required to ensure that all the interacting vehicles are included in the search area. For dynamic search area method search length and width change with time. In the present study, dynamic search area as a function of current and interacting vehicle characteristics is considered.

Case 1: Frontal search area

Search length : The frontal search area is used for taking overtaking and passing decisions when the vehicle catches up with the slower vehicle. The decision point for overtaking is when the vehicle is behind the slower vehicle by a distance equal to the sum of head length of the faster vehicle and tail length of the slower vehicle, as shown in the Figure 3.10. Let search length (x) of the search area is represented as:

$$x = l_1 + l_2 \tag{3.20}$$

It is essential that the component lengths l_1 and l_2 be estimated to incòrporate all possible eventualities. Length l_1 is estimated for the case assuming that the vehicle ahead is stopped and the current vehicle accelerates to its maximum capability.

$$l_1 = \frac{V_{ec}^2}{2.0 * max\_dec} \tag{3.21}$$

where V_{ec} is a maximum expected speed in the next scanned time interval. Length l_2 is estimated as maximum possible tail length in the given traffic mix. It is taken as maximum of tail lengths for all vehicle types.

Further to ensure that searched area does not miss any interacting vehicles the length scanned is taken twice of the computed distance.

$$sl_{fa} = 2.0(l_1 + l_2) \tag{3.22}$$

where sl_{fa} is a search length for the frontal search area.
Search width : The width of the frontal area is sum of the current vehicle width and its lateral spacing on both the sides. This is defined as:

$$sw_{fa} = (v\_w + 2.0 * l\_s) \tag{3.23}$$

where sw_fa = width of the frontal search area;
v_w = vehicle width; and
l_s = lateral space.

For taking overtaking decision, required lateral space is calculated depending upon expected speed at the time of overtaking. For forward movement, expected speed in the next scanned time is computed by taking maximum acceleration rate. Possible maximum acceleration rate is calculated by solving force equation of motion at the current speed. Therefore, this criterion ensures that vehicle gets required lateral spacing when it accelerates.

Case 2: Left frontal search area

Search length : Same as in Case 1

Search width : Width of the left frontal search area to be scanned is

$$sw_{lfa} = (max\_wid + m\_l\_s) \tag{3.24}$$

where sw_{lfa} = width of the left frontal search area;
max_wid = maximum width for all types of vehicles present in heterogeneous traffic mix; and
m_l_s = maximum lateral space required by current vehicle when it is interacting with any type of vehicle present in heterogeneous traffic mix.

Case 3: Right frontal search area

Search length : Same as in Case 1

Search width : Same as in Case 2

Case 4: Rear search area

The rear search area is used for taking yielding decision, when vehicle is caught up by the faster moving vehicle. The decision of yielding starts at the point when the the vehicle is ahead of faster vehicle by a distance equal to the sum of head length of faster vehicle and tail length of the slower vehicle, as shown in Figure 3.10.

Search length : It is essential that the component length l_1 and l_2 be estimated to incorporate all possible eventualities. l_1 is taken as maximum of maximum head length for all the vehicle types present in the simulated traffic mix. The maximum head length of a given vehicle type is calculated by considering its own maximum speed, i.e., its free speed and speed of front vehicle is taken as speed of current vehicle. Component length l_2 of the current vehicle (vehicle in reference) is calculated by considering speed attained by using its own maximum acceleration rate. Further to ensure that rear searched area does not miss any interacting cases, the scanned length is taken as twice of the computed distance $(l_1 + l_2)$.

$$sl_{ra} = 2.0(l_1 + l_2) \tag{3.25}$$

Search width :

$$sw_{ra} = v\_w + 2.0 * l\_s \tag{3.26}$$

where sw_{ra} = Width of the rear search area; and
l_s = lateral space computed at its own current speed.

Case 5: Left rear search area

Search length : Same as in Case 4

Search width : Same as in Case 2

Case 6: Right rear search area

Search length : Same as in Case 4

Search width : Same as in Case 2

3.10 INDIVIDUAL VEHICLE MOVEMENT CHARACTERISTICS

The flow process being dynamic, the stream logic for a vehicle will change with time depending upon its position, speed, status with relation to other vehicles. The flow logics in this model are classified as:

- Free flow process
- Constrained flow process
- Overtaking/passing flow process
- Yielding flow process

3.10.1 Free Flow Process

In free flow situation, the vehicle moves at a uniform free speed of the road block. A vehicle is said to be in free flow mode in the following situations:

- Free speed of the current vehicle is less than the speed of the vehicle ahead. In this case the spacing between the two will increase with time and the current vehicle can move freely till some other interaction is encountered.
- If the current vehicle is moving faster than the vehicle ahead in the same lane the spacing between the two decides whether the current vehicle will move freely for some more time or the following operation is to start. The current vehicle can move freely at any instant if the available space headway is more than the sum of the head length of the current vehicle and the tail length of the vehicle ahead.

Determination of free speed

To test the ability of a vehicle to reach its free speed v_{fr}, v is set to equal to current speed of the vehicle in the force equation of motion (equation 3.8), and acceleration is determined. Following two cases of acceleration capability of the vehicle can arise:

a $\leq$ 0: In this case, it is not possible for vehicle to accelerate. Therefore, the vehicle can move with its current speed 'v' or can decelerate in the given road block.

a $\geq$ 0: In this case, it is possible for vehicle to accelerate or decelerate in the following ways:

I Current speed of the vehicle is less than the free speed of the vehicle, i.e., $v < v_{fr}$, the vehicle will accelerate to attain the free block speed.

II Current speed of the vehicle is equal to free speed of the vehicle, i.e., $v = v_{fr}$, since vehicle has attained its free speed so it will not accelerate further.

III Current speed of the vehicle is greater than the free speed of the vehicle, i.e., $v > v_{fr}$, so it is not possible for vehicle to continue to move at its current speed. Therefore, it retards uniformly from speed v to v_{fr}.

3.10.2 Constrained Flow Logic

If conditions of free flow do not hold at any instant, then the current vehicle reduces its speed to that of the vehicle ahead and starts following. Constrained flow situation of the vehicle can be divided into following three parts:

- Following started
- Following continued
- Following terminated

When a vehicle enters the constrained flow status, it starts decelerating (following started) and finally follows the slower vehicle ahead (following continued). While following, a driver always searches for opportunities to overtake. Overtaking can be performed by either moving to the right or when vehicle ahead yields to the left, in order to provide space for passing. In some situations, constrained vehicle tries to overtake from the left. If a vehicle performs overtaking, then following is terminated (following terminated mode), otherwise it continues in the same state (following continued).

In the constrained flow situations, car following model is used to calculate acceleration rate based on relationship with the leading vehicle. The space headway polynomials derived from the field data are also ~~be~~ used to compute minimum space headway between two interacting vehicles. These submodels are used in following unidirectional traffic flow situations:

- Following a slower vehicle;
- Yielding to the left in order to provide space for faster vehicle to perform passing operation.

Car-Following Model Approach

Forbes (1958, 1963, 1968) firstly approached car-following theory by considering the reaction time needed by a driver of following vehicle to perceive the need to decelerate and apply brakes. Forbes had conducted many field studies and found that minimum time gaps depend upon driver and site (location). He also found that as the speed of following vehicle increases associated minimum time headway and distance headway increases.

Further the car-following theories developed by researchers of General Motors Corporation were much more extensive and are of importance because these theories were calibrated and validated by the field studies. The research team of General Motors Corporation had developed five generations of car-following models.
The basic equation of the model is of the form

$$Response(t+T) = Senstivity * Stimulus(t) \tag{3.27}$$

In the first type of model, assumption was made that sensitivity terms remain constant and the model can be represented as:

$$\ddot{x}_{n+1}(t+T) = \alpha(\dot{x}_n t - \dot{x}_{n+1}(t)) \tag{3.28}$$

where $\ddot{x}_{n+1}(t+T)$ = acceleration of following vehicle (n+1) at time (t+T);
$\dot{x}_n(t)$ = velocity of lead vehicle (n) at time t;
$\dot{x}_{n+1}(t)$ = velocity of following vehicle (n+1) at time t;
T = reaction time of following vehicle driver;
α = sensitivity.

Some of the researchers (Gazis, et al., 1959, 1961) proposed that there should be two values of sensitivity depending upon the separation between following and lead vehicle. These investigations lead to the non-linear car-following model in which sensitivity (α) can be defined as

$$\alpha = \frac{\alpha_0}{d} = \frac{\alpha_0}{x_n(t) - x_{n+1}(t)} \tag{3.29}$$

where $x_n(t)$ = position of lead vehicle (n) at time t;
$x_{n+1}(t)$ = position of lead vehicle (n+1) at time t;
d = space headway between the two vehicles;
α_0 = sensitivity constant having unit of velocity.

$$\ddot{x}_{n+1}(t+T) = \frac{\alpha_0}{x_n(t) - x_{n+1}(t)}[\dot{x}_n(t) - \dot{x}_{n+1}(t)] \tag{3.30}$$

Generalised car-following model can be represented as

$$\ddot{x}_{n+1}(t+T) = \alpha_{l,m}\frac{[\dot{x}_{n+1}(t+T)]^m}{[x_n(t)-x_{n+1}(t)]^l}[\dot{x}_n(t)-\dot{x}_{n+1}(t)] \tag{3.31}$$

The car-following models were evolved based on the observations and field studies made for homogeneous motorised traffic. Most of the sitesselected for conducting experiments and data collection were freeways or multi-lane highways having unidirectional flow. In the previously conducted car-following studies roads selected have lane discipline. For the complex heterogeneous traffic having significant proportion of non-motorised vehicles, there is a need for developing a separate car-following model. The present study, however, does not envisage the conduct of an exclusive car-following study due to time constraint. However, a linear car-following model is adapted for this simulation model.

Space Headway Polynomial Approach Space headway polynomials are used in calculating minimum spacing required by the vehicle in constrained situation. It is assumed that minimum spacing required by a constrained vehicle is a function of its own speed and the speed of the vehicle ahead.

$$sp_{const} = f(v_{fr}, v_{re}) \tag{3.32}$$

where sp_{const} = minimum spacing in constrained situation;
v_{fr} = speed of front (lead) vehicle; and
v_{re} = speed of rear (following) vehicle.

Space headway polynomials are fitted on data sets collected for different type of vehicles interactions. Procedure for predicting vehicle position in the next time interval is given below:

Let
$P_l(t+\Delta t)$ = position of the lead vehicle at time $(t+\Delta t)$
L_l = length of the lead vehicle
$P_f(t)$ = position of the following vehicle at time (t)
$sp_{const}(t+\Delta t)$ = minimum spacing at time $(t+\Delta t)$ required by the following vehicle in a constrained situation
$d_{fmax}(\Delta t)$ = maximum distance which following vehicle can move in a constrained situation in the next time interval (Δt)
= $P_l(t+\Delta t) - L_l - sp_{const}(t+\Delta t) - P_f(t)$.

By using maximum distance which vehicle can move in the time interval Δt, lateral and longitudinal coordinates, speed and acceleration of the following vehicle can be estimated.

Certain checks are also made on the acceleration rate obtained from the car following model or space headway polynomial approach to ensure that acceleration rate falls within the permissible range. These checks are:

Check I Acceleration obtained from the car following model should be less than maximum acceleration capability of the vehicle. Maximum acceleration capability of the vehicle

at an instant of time is obtained by passing required vehicle attributes in force equation of motion (equation 3.8). Two cases can arise:

Case I: acceleration obtained $\geq$ maximum acceleration capability: acceleration = maximum acceleration capability

Case 2: acceleration obtained < maximum acceleration capability: In this case two conditions can again arise depending upon maximum deceleration rate of the vehicle. These conditions are:

Condition I: acceleration obtained $\geq$ maximum deceleration rate: acceleration = acceleration obtained

Condition II: acceleration obtained < maximum deceleration rate: acceleration = maximum deceleration rate

Check II Speed obtained by using acceleration rate should be less than maximum speed limit (minimum of road block speed limit, and free speed). If speed obtained is greater, then vehicle will modify its acceleration rate by decreasing its speed to the maximum speed limit.

Check III Vehicle will ensure that it will not collide with the vehicle ahead. This condition can be stated as emergency regime. In the emergency regime space headway is less than the pre-determined threshold value (sp_hd_{lower}). This threshold value is sum of head length and tail length computed by deceleration rate higher than normal. If available space headway is less than the predetermined threshold value, then vehicle will decelerate in accordance with the required safe space headway.

At every time interval of Δt(one second) vehicle looks for an opportunity to come out of constrained flow situation. This is possible when any of the following conditions is true.

- Vehicle ahead accelerates
- Vehicle ahead shifts to the left giving adequate space to following vehicle for passing without shifting to the right
- Vehicle itself moves to the right and finds adequate space for performing overtaking operation

3.10.3 Overtaking Sequences (Flying and Accelerative Overtakings)

If catching up vehicle A is not allowed to pass in its road space along the width i.e., when either vehicle B rejects to move to the left (yielding probability is below critical level of acceptance), or when B moves to the left but does not provide adequate road space to the

vehicle A for safe passing, vehicle A would look for space on right. If A finds that space available is more than required for overtaking, it starts overtaking without reducing its speed. This is defined as a flying overtaking operation. If flying overtaking is not performed then vehicle A starts following B by reducing its speed. In the subsequent time intervals, vehicle A looks for an acceptable space on the right for overtaking. Once such space is available it starts overtaking by accelerating. This type of overtaking is defined as accelerative overtaking.

Flying/accelerative overtaking operations are illustrated in Figure 3.14. Figure 3.14a shows the start of interaction between overtaking vehicle (A) and overtaken vehicle (B). Space available on the left of vehicle B is not sufficient to allow passing. Because of this, vehicle A searches space right of vehicle B to perform overtaking operation. Vehicle A will move to the right with certain probability. Figure 3.14b shows vehicle A performing flying/accelerative overtaking operation and is parallel to overtaken vehicle B. Figure 3.14c shows flying/accelerative overtaking completed by vehicle A and it returns to its desired space.

Figure 3.15 shows multiple flying/accelerative overtaking performed by the vehicle A. Where vehicle A desires to return to its desired space after overtaking vehicle B, it finds another slow moving vehicle C on the left. Therefore, it is necessary for vehicle A to overtake vehicle C also in order to come to its desired space. Completion of multiple overtaking operation is illustrated in Figure 3.15 c and vehicle A comes to its desired space after overtaking vehicle C.

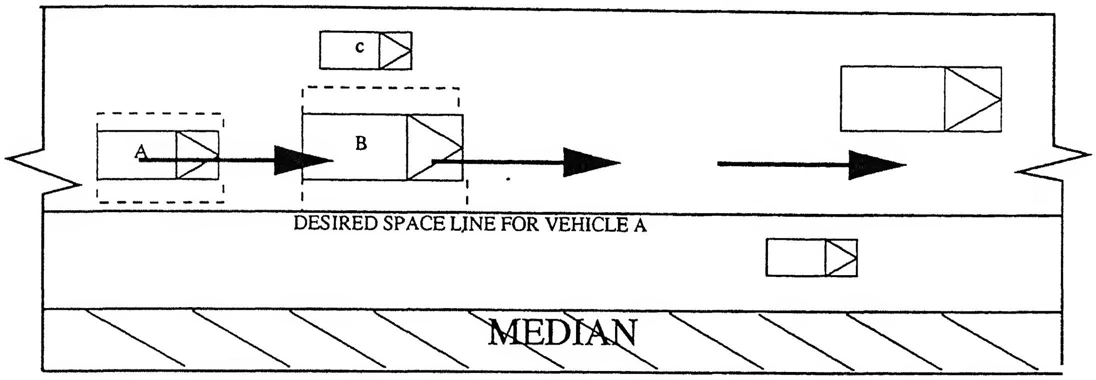
Sometimes vehicles overtake others without interaction. This happens when intersection of rear search area of overtaken vehicle and front search area of overtaking vehicle is NULL. Such type of overtaking is termed as ordinary overtaking, e.g., in Figure 3.15, vehicle A overtakes vehicle E.

Decision making in flying overtaking process can also be explained with the help of Figure 3.16, which shows the space-time diagrams of overtaking and overtaken vehicles. When faster vehicle catches up with a slower moving vehicle, two vehicles starts interacting at point D. At this point of time, separation between the two interacting vehicles is less than or equal to maximum threshold spacing (l_d), where l_d is sum of head length of the overtaking vehicle, and tail length of the overtaken vehicle. This interaction distance is given by

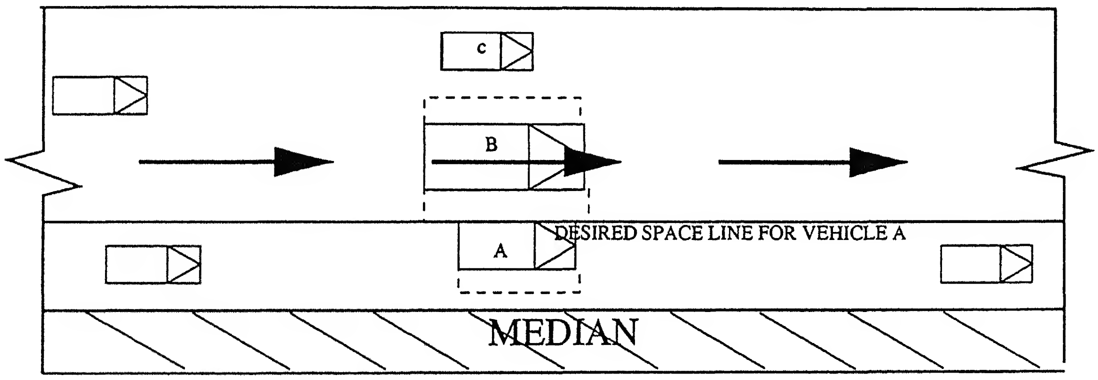
$$l_d = f(hl_{ovt}, tl_{ovn}) \tag{3.33}$$

Maximum threshold spacing is further modified with coefficient (mul_coff).

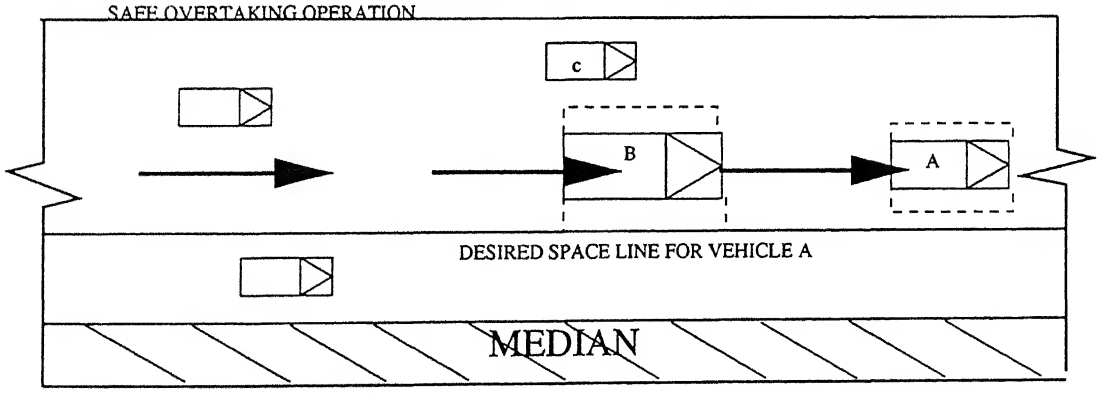
$$l_d = mul\_coff(hl_{ovt} + tl_{ovn}) \tag{3.34}$$



(a) FASTER VEHICLE A CATCHING UP WITH SLOWER VEHICLE B

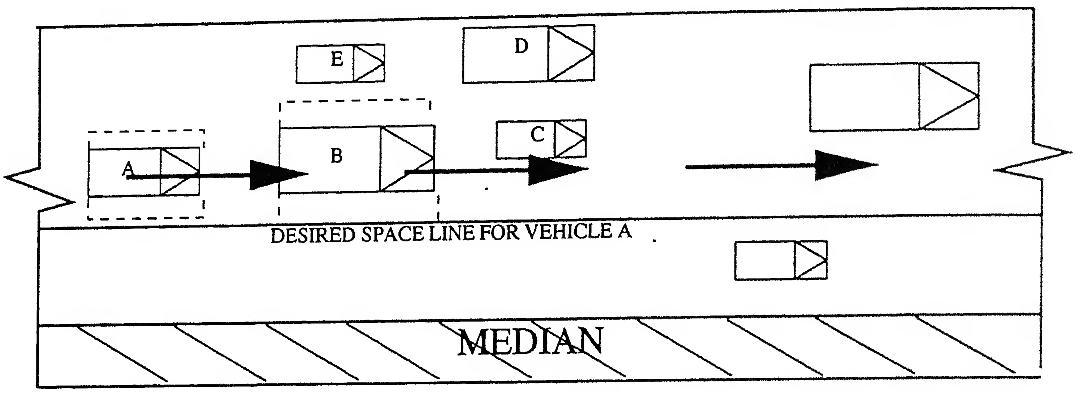


(b) A PERFORMING FLYING/ACCELERATIVE OVERTAKING WITH VEHICLE B AND C, VEHICLE COMING OUT OF DESIRED SPACE TO GET REQUIRED LATERAL CLEARANCE FOR SAFE OVERTAKING OPERATION

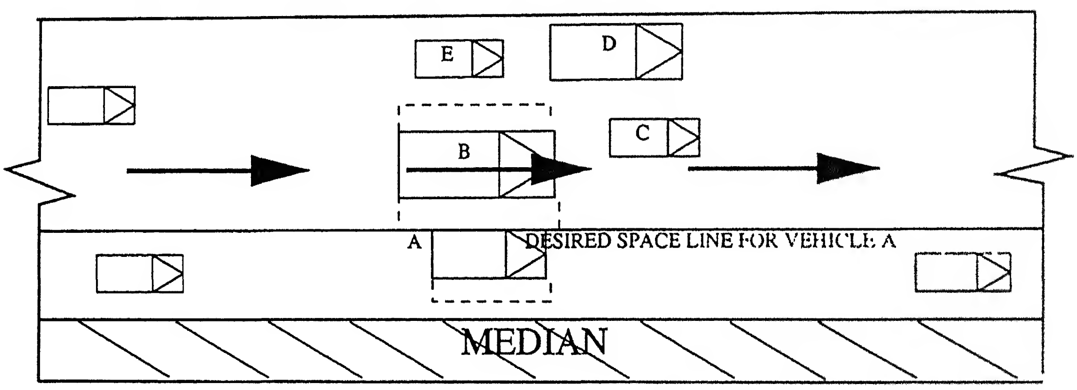


(c) FLYING/ACCELERATIVE OVERTAKING COMPLETED, VEHICLE A COMING BACK IN ITS DESIRED SPACE

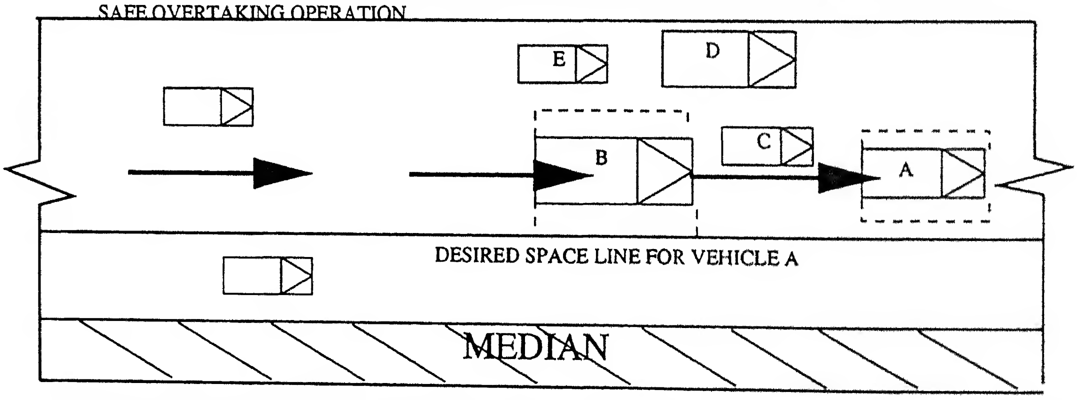
Figure 3.14: Decision Process of Flying/Accelerative Overtaking



(a) FASTER VEHICLE A CATCHING UP WITH SLOWER VEHICLE B



(b) A PERFORMING FLYING/ACCELERATIVE MULTIPLE OVERTAKING WITH VEHICLE B AND C, VEHICLE COMING OUT OF DESIRED SPACE TO GET REQUIRED LATERAL CLEARANCE FOR SAFE OVERTAKING OPERATION



(c) FLYING/ACCELERATIVE MULTIPLE OVERTAKING COMPLETED, VEHICLE A COMING BACK IN ITS DESIRED SPACE

Figure 3.15: Decision Process of Flying/Accelerative Multiple Overtaking

where l_d = Interaction distance, which is separation between overtaking and overtaken vehicles;
hl_{ovt} = head length of overtaking vehicle;
tl_{ovn} = tail length of overtaken vehicle;
mul_coff = multiplying coefficient.

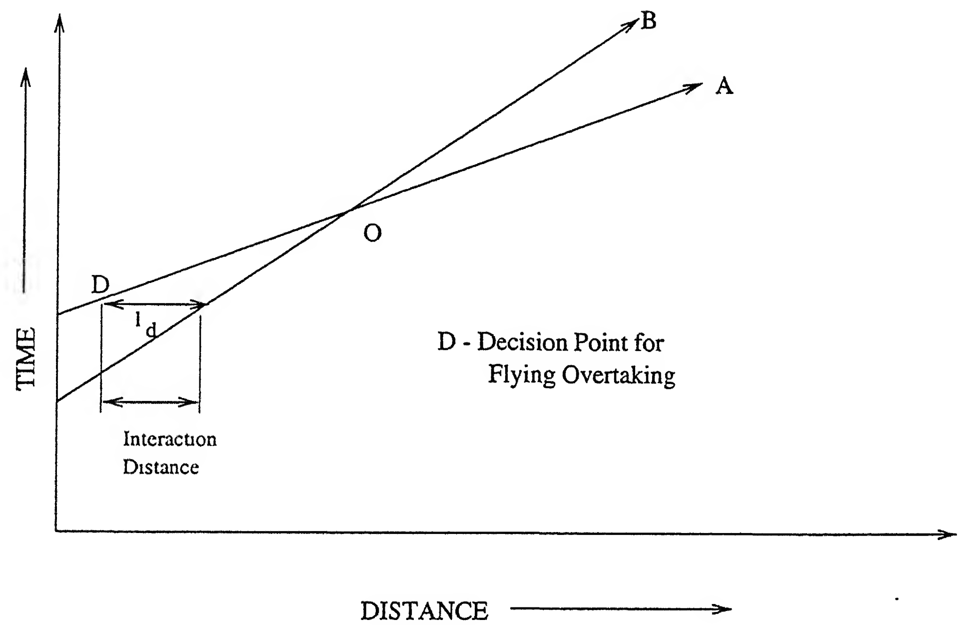


Figure 3.16: Time Space Diagram for Flying Overtaking Process

At point D vehicle scans frontal search area and identifies the vehicles which are interacting. In this case vehicle A is interacting with vehicle B. Separation between interacting vehicles is within threshold spacing. Therefore, at this point of time vehicle A will decide to overtake or not. The decision making, however, is not deterministic but is of probabilistic nature. Probability of overtaking dependsupon the attributes of interacting vehicles such as free speed, lateral and longitudinal positions, lateral spacing, etc.

The overtaking behaviour of a vehicle is dependent on the difference between free speeds (FS) of overtaking and overtaken vehicles, and available inter-vehicular lateral spacing (IVLS) between the two interacting vehicles at the time of decision making. The decision, however, is not deterministic but represented by probability function. If the probability is one then overtaking will be done certainly and if probability is zero then overtaking is not possible. For probability between 0 to 1, there is a possibility of overtaking depending on the value of probability p. (i.e. the higher value of p the greater the possibility) of overtaking.

Two probability functions are constructed one is based on difference in free speeds (ΔFS) and other is based on inter-vehicular lateral spacing (IVLS). Based on the expert information we assign a minimum $\Delta FS_{MIN_{OV}}$ and assign zero probability to this point. Similarly there is a maximum $\Delta FS_{MAX_{OV}}$ above which overtaking is certain (probability = 1). In between minimum and maximum ΔFS, a linear probability function is assumed. The probability function shown in Figure 3.17 is expressed as:

$$prob_1 = \begin{cases} 0 & x < \Delta FS_{MIN_{OV}} \\ \frac{x - \Delta FS_{MIN_{OV}}}{\Delta FS_{MAX_{OV}} - \Delta FS_{MIN_{OV}}} & \Delta FS_{MIN_{OV}} \leq x \leq \Delta FS_{MAX_{OV}} \\ 1 & x > \Delta FS_{MAX_{OV}} \end{cases} \tag{3.35}$$

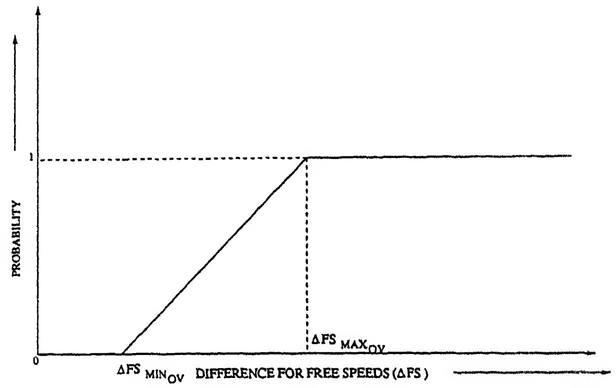


Figure 3.17: Overtaking Probability Function for Free Speed

The permissible minimum and maximum difference between the free speeds of the overtaking and overtaken vehicles need to be calibrated.

For the inter-vehicular lateral spacing (IVLS) criterion, if the IVLS is less then minimum inter-vehicular lateral spacing ($IVLS_{MIN_{OV}}$), the probability for overtaking is zero. If IVLS is more then maximum inter-vehicular lateral spacing ($IVLS_{MAX_{OV}}$), the probability is one. For in between values, probability varies linearly as shown in Figure 3.18. Mathematically this can be written as

$$prob_2 = \begin{cases} 0 & x < IVLS_{MIN_{OV}} \\ \frac{x - IVLS_{MIN_{OV}}}{IVLS_{MAX_{OV}} - IVLS_{MIN_{OV}}} & IVLS_{MIN_{OV}} \leq x \leq IVLS_{MAX_{OV}} \\ 1 & x > IVLS_{MAX_{OV}} \end{cases} \tag{3.36}$$

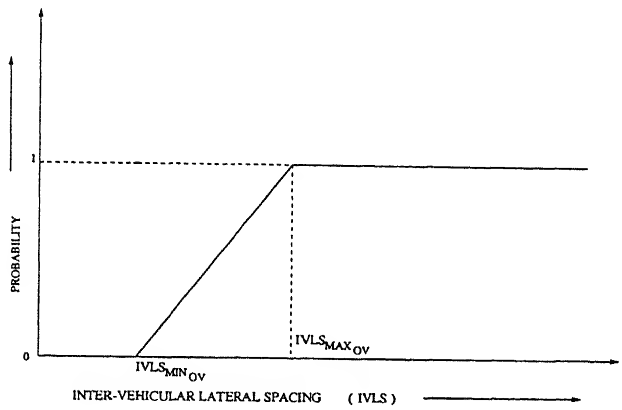


Figure 3.18: Overtaking Probability function for Inter-Vehicular Lateral Spacing

The minimum and maximum value of inter-vehicular lateral speed for different combinations of overtaking and overtaken vehicles need to be calibrated.

The probability of overtaking is represented as the minimum of the above two probabilities. This can be represented as

$$prob_{ov} = min(prob_1, prob_2) \tag{3.37}$$

where $prob_{ov}$ = probability of overtaking;
$prob_1$ = probability of overtaking by considering free speed of the interacting vehicles; and
$prob_2$ = probability of overtaking by considering the available inter vehicular lateral spacing between the interacting vehicles;

If the generated uniformly distributed random number is less than or equal to the required probability of overtaking ($prob_{ov}$) then decision of overtaking is accepted. In the present case shown in Figure 3.16 vehicle A decides to overtake vehicle B. Amount of required right lateral shift by vehicle A in order to overtake vehicle B without reducing its speed is determined. It is assumed that overtaking speed is a function of overtaken speed and inter vehicular lateral spacing. This can be represented as:

$$ovt_{sp} = f(ovn_{sp}, IVLS_{OV}) \tag{3.38}$$

where ovt_{sp} = speed of the overtaking vehicle;
ovn_{sp} = speed of the overtaken vehicle; and
$IVLS_{OV}$ = inter-vehicular lateral spacing at the time of overtaking.

By solving equation 3.38 numerically, for the known expected overtaking speed and overtaken speed, expected value of inter-vehicular lateral spacing for overtaking operation is calculated.

Depending upon the lateral and longitudinal coordinates of the overtaking and overtaken

vehicles and required inter-vehicular lateral spacing, value of right lateral movement required by the overtaking vehicle is calculated. If overtaking decision is true then vehicle moves to the right for performing safe overtaking operation. For getting required right lateral shift, vehicle searches the right frontal and rear areas (Figure 3.13) to ensure that after changing its lateral position vehicle maintains adequate space headway with the interacting vehicles present in these areas. As shown in Figure 3.16, vehicle A performs overtaking without reducing its speed, it means that vehicle gets required lateral movement and satisfies space headway criteria with the interacting vehicles present in right frontal and rear areas.

After completion of the overtaking operation, if it is required for overtaking vehicle to shift to the left in order to come in its desired area, then vehicle will search left frontal and rear areas (Figure 3.13). If vehicles are present in the search areas and interacting with the current vehicle, then vehicle will check for space headway criteria. If space headway criteria is satisfied, then vehicle will come in his desired area. In flying overtaking, if overtaking vehicle is not moving initially at its free speed, then it can accelerate in order to attain its free speed during overtaking process.

As shown in Figure 3.19 vehicle A performs multiple flying overtaking with vehicles B and C. Vehicle A first performs flying overtaking with vehicle B. After the completion of this flying overtaking operation, vehicle A finds another slow moving vehicle C in front. Logical decisions involved in the multiple flying overtaking process are same as explained above.

Decision making for accelerative overtaking process is explained with the help of Figure 3.20, which shows the space-time graphs of the overtaking and overtaken vehicles A and B. At point i_1 vehicle A starts interacting with vehicle B, which is directly in front. Searching and probabilistic overtaking decision making process is same as described in flying overtaking sequence case. In the portion($i_1 i_2$) vehicle A tries to perform flying overtaking operation with vehicle B, but does not succeed. At the point i_2 vehicle finds that available longitudinal spacing is not adequate to maintain its current speed due to low speed of vehicle B. Therefore, from point i_2 vehicle A will start following B. In order to maintain adequate longitudinal spacing vehicle A will decelerate up to point i_3. Deceleration rate is calculated by scanning frontal search area. After the decision point i_3 (following continued) vehicle A enters into the following continued mode. In the portion $i_3 i_4$, vehicle A, takes decision at the regular time intervals. Overtaking decision making process is probabilistic like the flying overtaking sequences. At point i_4, vehicle finds that probability of overtaking is above the critical level of acceptance. Amount of lateral movement required by the vehicle is calculated.

To get required lateral movement vehicle A scans right and left frontal search areas to check longitudinal spacing with interacting vehicles. In the portion $i_4 i_5$ vehicle A overtakes

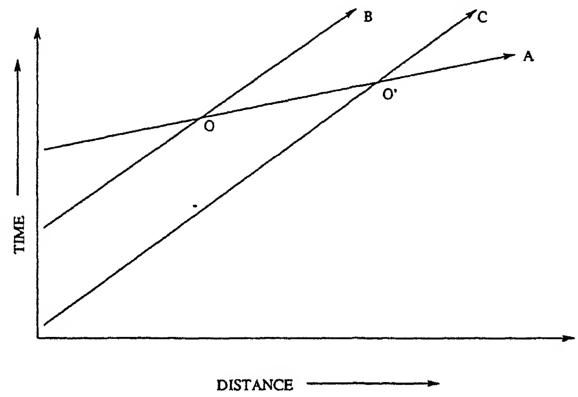


Figure 3.19: Space-Time Diagram of Overtaking and Overtaken Vehicles during Multiple-Flying Overtaking Process

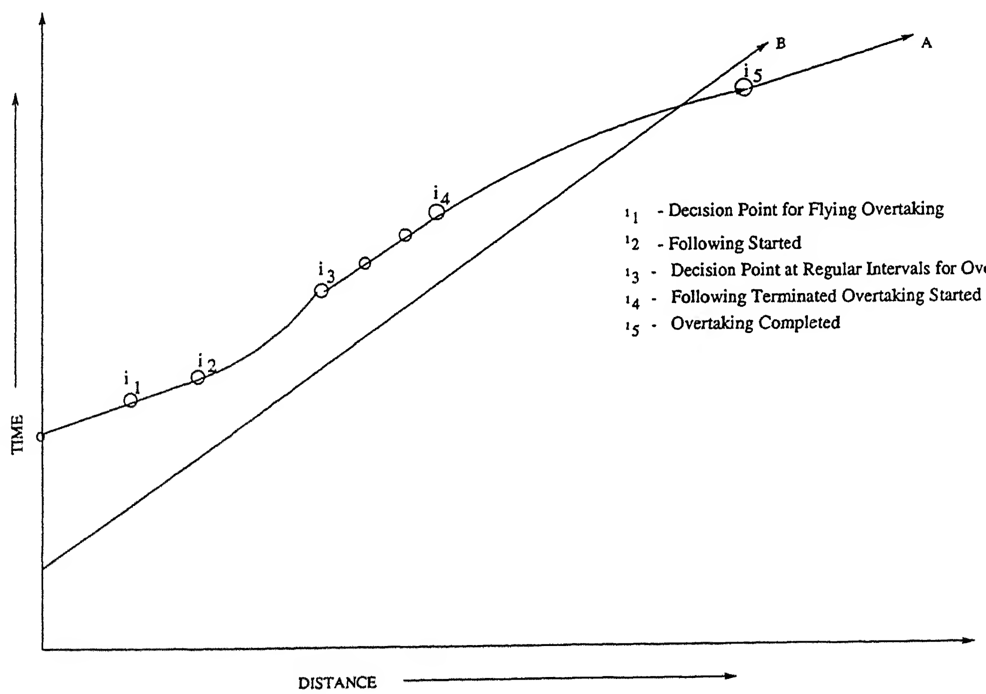


Figure 3.20: Space-Time Diagram of Overtaking and Overtaken Vehicles during Accelerative Overtaking Process

vehicle B and accelerates its speed to free speed. At point i_5 vehicle A attains its free speed and moves in free flow mode.

3.10.4 Yielding and Passing Sequences

When a vehicle B is caught up from behind by a faster vehicle A, and vehicle A is present in rear search area of vehicle B, then vehicle B tends to yield to permit passing.

Passing manoeuver is illustrated in Figure 3.21. Figure 3.21a shows start of interaction between overtaking vehicle (A) and overtaken vehicle (B). In Figure 3.21b, slow moving vehicle B finds that amount of road space available on the left is adequate for yielding. Therefore, vehicle B yields to the left by required amount and vehicle A performs overtaking operation. Figure 3.21c shows that passing manoeuver performed by vehicle A is complete and vehicle B comes to its original lateral position as occupied at the time of interaction.

Decision making involved in passing process is almost identical to that of overtaking process. Maximum threshold spacing for yielding decision is same as in overtaking process. The yielding behaviour of front vehicle is stochastic in nature and is also dependent on the difference between free speed of front and rear vehicles and inter-vehicular lateral spacing between the two vehicles. It is considered that if the ΔFS is more then some specified value (ΔFS_{MAX_Y}), the front vehicle will definitely yield and if it is less then specified minimum value (ΔFS_{MIN_Y}) the vehicle will not yield. The probability function as shown in Figure 3.22, is stated mathematically as

$$yield\_prob_1 = \begin{cases} 0 & x < \Delta FS_{MIN_Y} \\ \frac{x-\Delta FS_{MIN_Y}}{\Delta FS_{MAX_Y}-\Delta FS_{MIN_Y}} & \Delta FS_{MIN_Y} \le x \le \Delta FS_{MAX_Y} \\ 1 & x > \Delta FS_{MAX_Y} \end{cases} \tag{3.39}$$

If the inter-vehicular lateral spacing is less than $IVLS_{MIN_Y}$ then the front vehicle will definitely yield and if the inter-vehicular lateral spacing is greater then $IVLS_{MAX_Y}$ then vehicle will not yield. Probability function as shown in Figure 3.23, is stated mathematically as

$$yield\_prob_2 = \begin{cases} 1 & x < IVLS_{MIN_Y} \\ \frac{IVLS_{MAX_Y}-x}{IVLS_{MAX_Y}-IVLS_{MIN_Y}} & IVLS_{MIN_Y} \le x \le IVLS_{MAX_y} \\ 0 & x > IVLS_{MAX_Y} \end{cases} \tag{3.40}$$

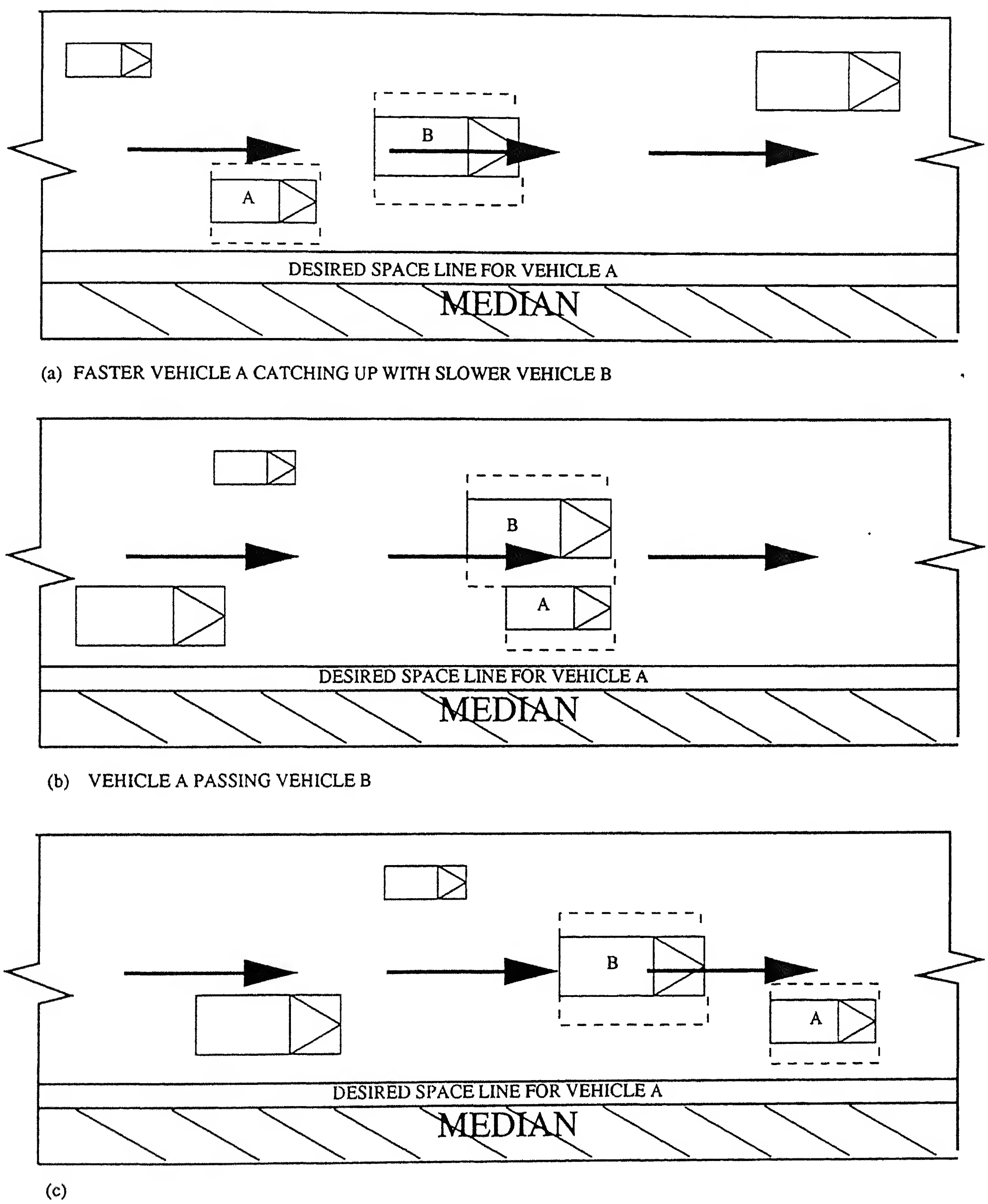


Figure 3.21: Decision Process of Passing Overtaking

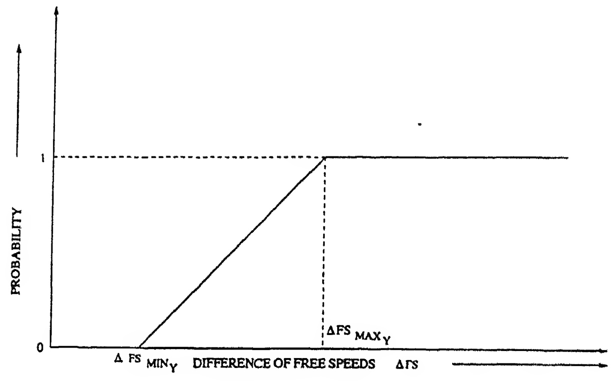


Figure 3.22: Yielding Probability Function for Free Speed (FS)

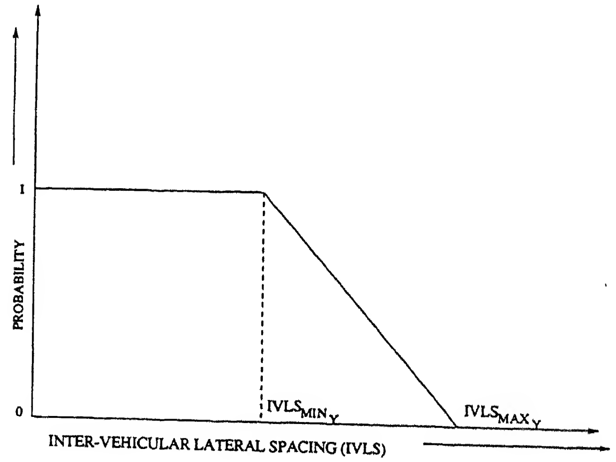


Figure 3.23: Yielding Probability Function for Inter-Vehicular Lateral Spacing

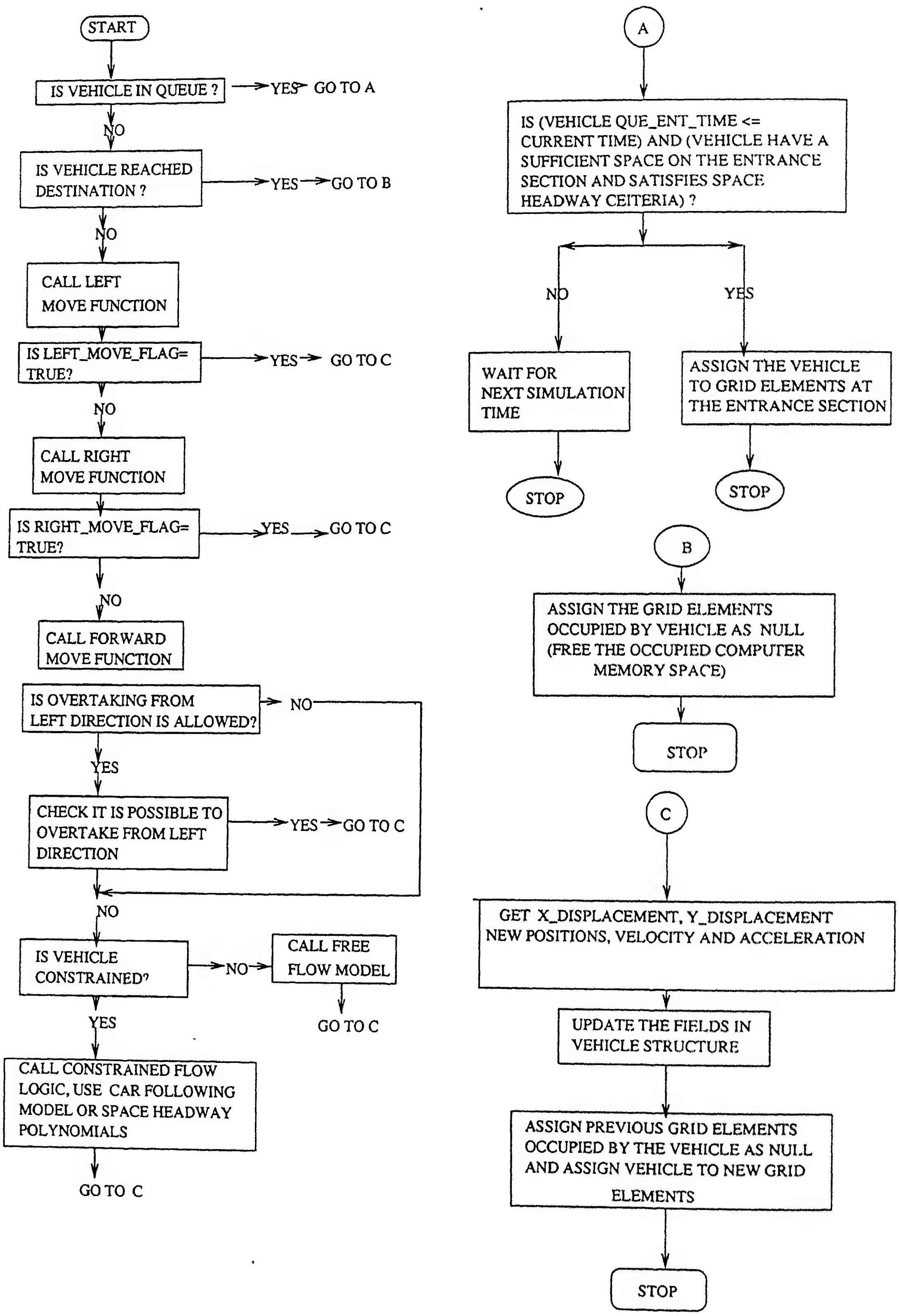


Figure 3.24: Flow Chart for Vehicle Movements

3.12 PROGRAMME SYSTEM FOR TRAFFIC SIMULATION MODEL

3.12.1 General

The special purpose simulation languages have been written for programming of specific type of systems. For example SIMULATE was designed for simulating large size economic systems and on the other hand GPSS (Bobiller, Kahan, and Probst, 1976) and SIMSCRIPT (Kivat et al., 1968) are suited for the system having queueing type of problems. The computer programme may be written in either a general purpose language or a special simulation language like GPSS (Schriber), SIMSCRIPT (Kivat), Dynamo (Pugh), Simulate (Hold) or SIMULA (Mitrani, 1982). The main advantage of these type of special purpose simulation language is that they require less time and effort to programme the problem but are suitable only for specific problem. With the help of these special purpose simulation languages it is difficult to model and programme complex traffic simulation problems. Therefore, in the present study universally accepted C language has been chosen for programming. Advantage of C programming language is that it is available on most of the operating systems and its portability is superior. Analysis approach involved in computer simulation of urban heterogeneous traffic are illustrated in flow chart given in Figure 3.25.

3.12.2 Computer Models

The overview of simulation programme system is given in Figure 3.26. The model has following submodels:

- Road generation submodel
- Traffic generation submodel
- Traffic simulation submodel
- Results processing submodels

The main programme is written in modular fashion, which provides ample scope of including new sub-models in the present simulation model. There are large number of subroutines written for traffic simulation model. The macro details and algorithm of some of the important subroutines used for traffic generation, road generation, traffic flow logic and statistical analysis are given.

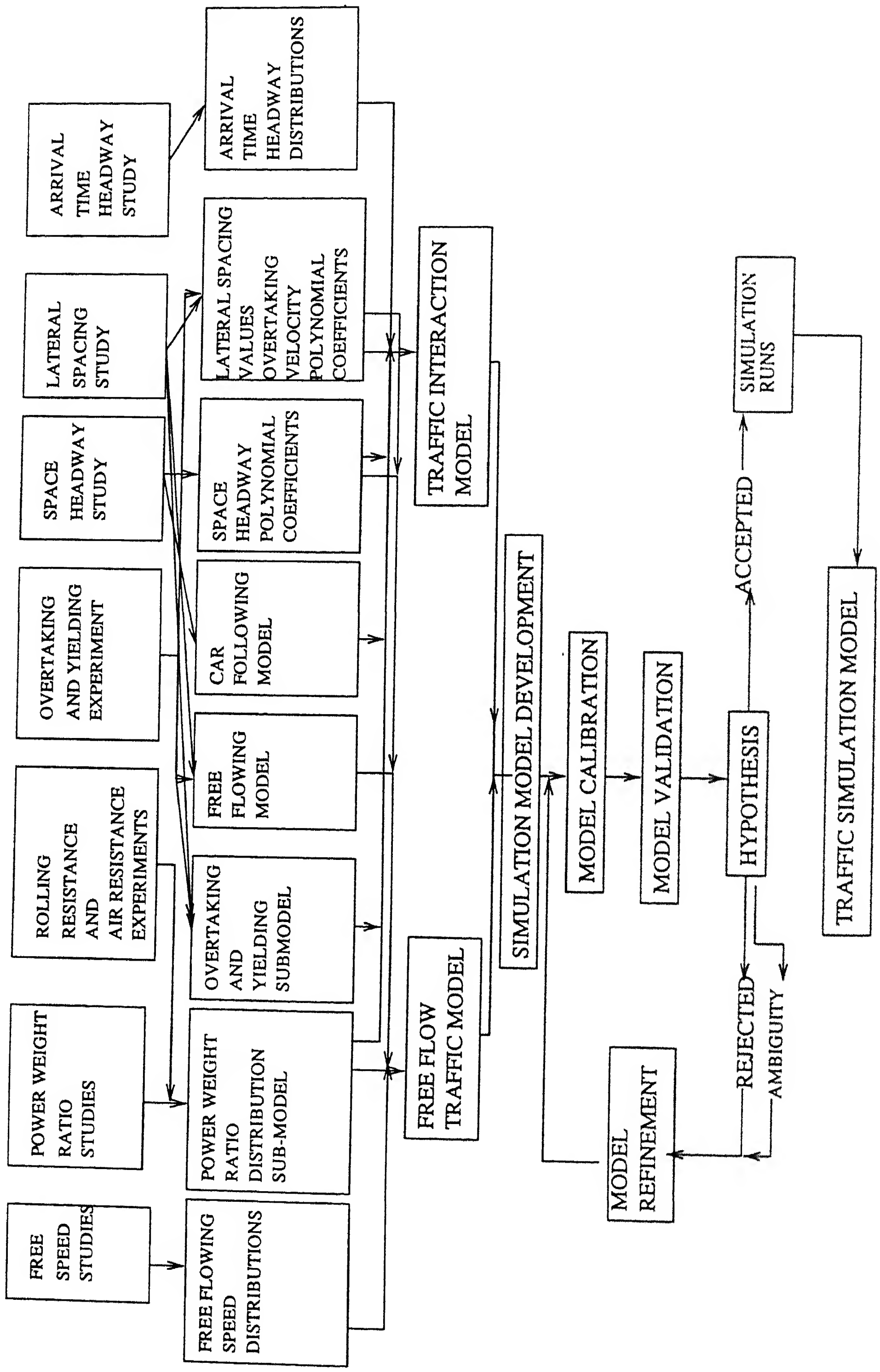


Figure 3.25: Analysis Approach

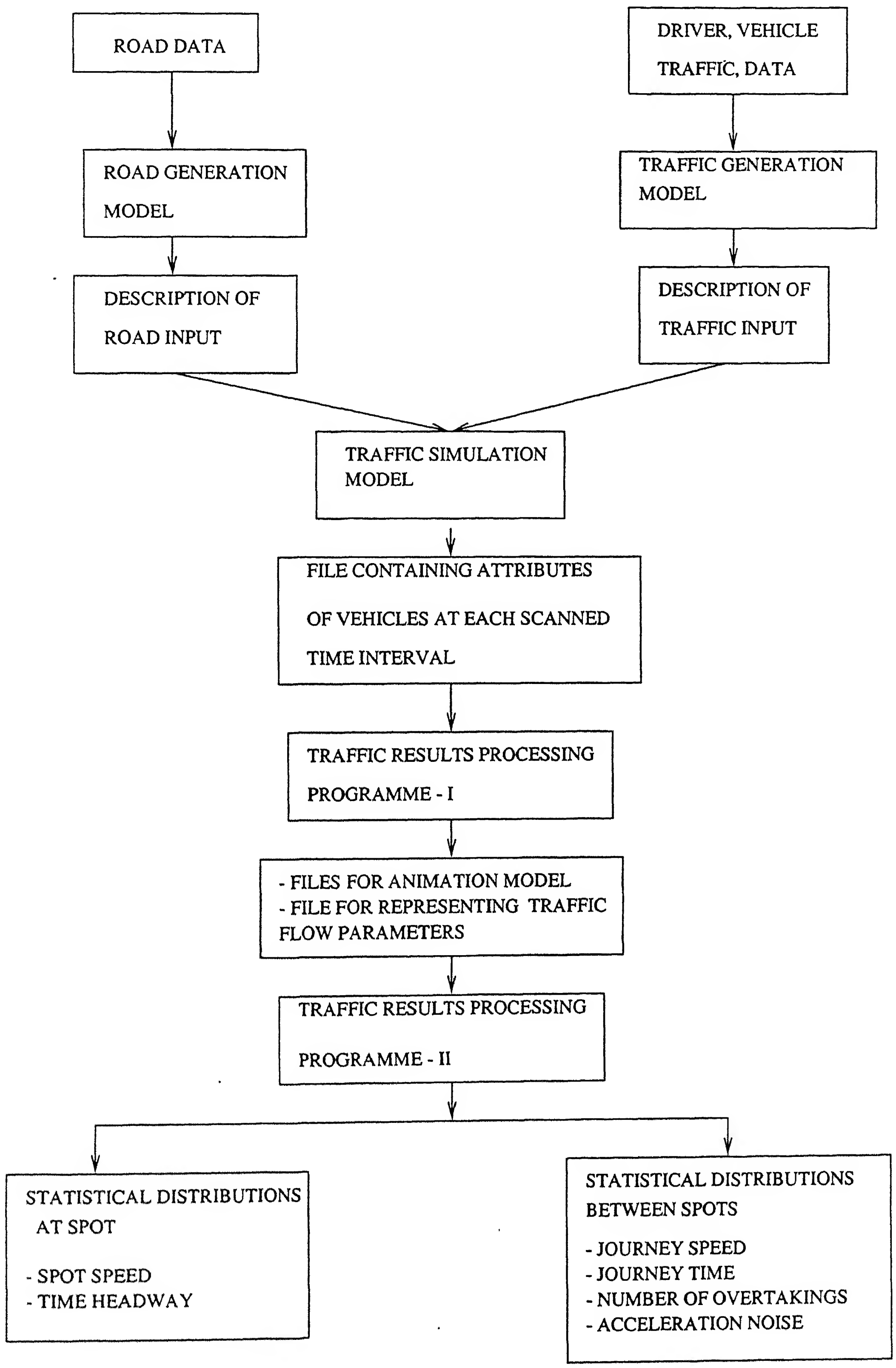


Figure 3.26: Broad Overview of Simulation Programme

3.12.3 Macro Algorithm for Main Traffic Simulation Programme

Main traffic simulation programme calls different submodels in a sequence. Flow chart of main traffic simulation programme is shown in Figure 3.27. Macro algorithm for traffic simulation programme is given in section A of appendix A.1.

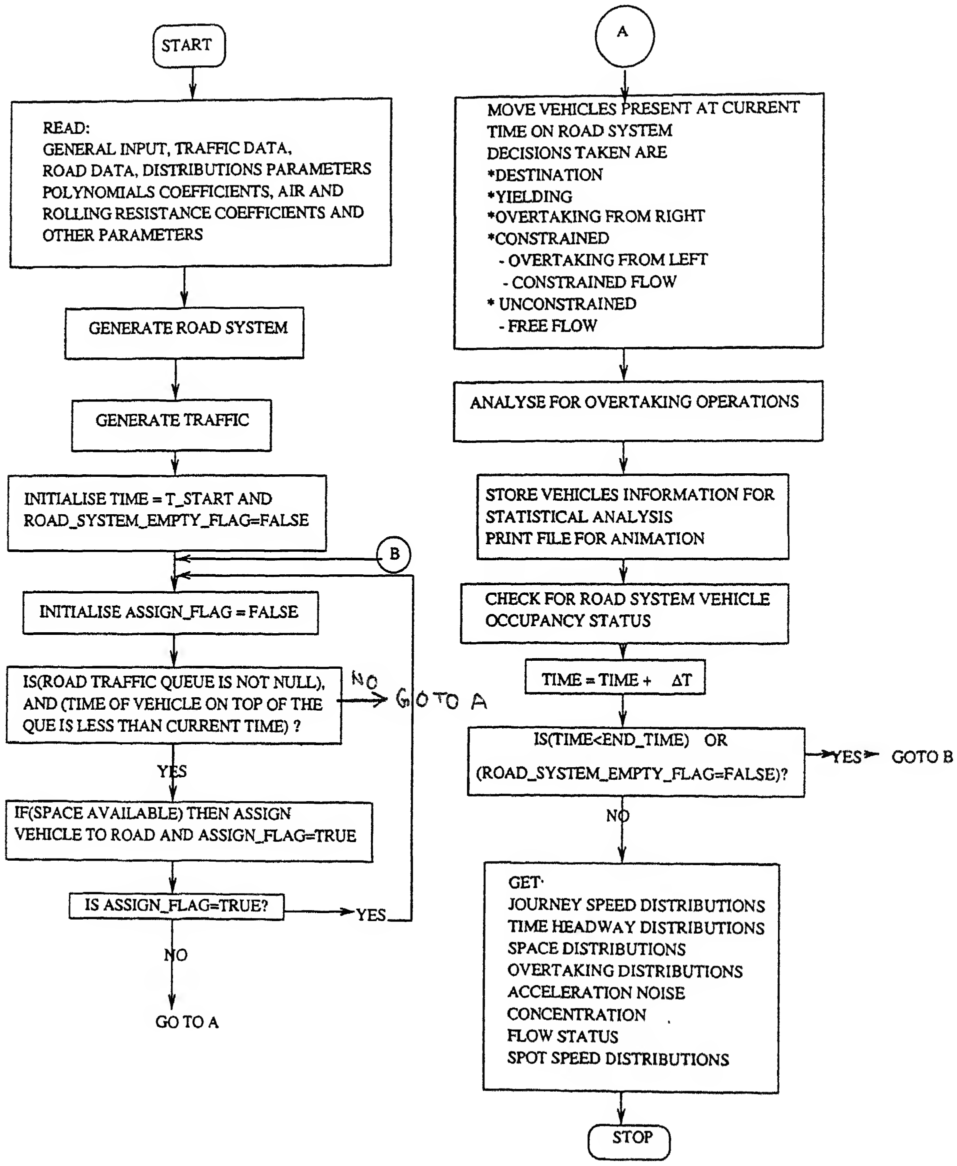


Figure 3.27: Flow Chart for Main Traffic Simulation Model

The programme works in the following way:
(i) Firstly file system for reading various inputsis opened.
(ii) Then the road generation process, is initiated.
(iii) Traffic generation process is initiated. Traffic generation submodel generates vehicles for given simulation time interval.
(iv) Time variable is initialised to start time and road_system_empty_flag is assigned as True. Order of movements performed and decisions taken by the vehicle depending upon its position on the road system and interaction with the vehicles present are illustrated in flow chart given in Figure 3.24.

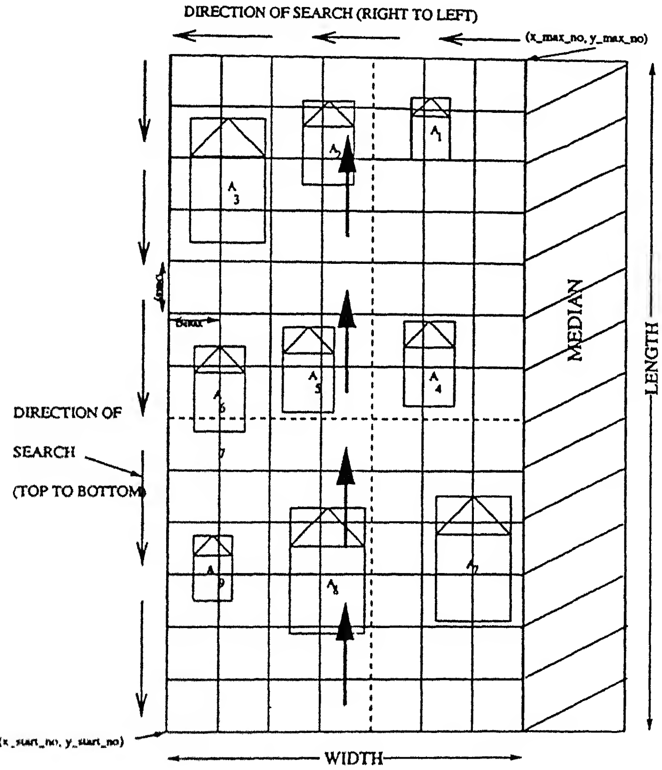


Figure 3.28: Order of Selection of Vehicles During Road Grid Elements Search in Computer Model

(v) Traffic queue is checked. If road traffic queue is not NULL and generation time of vehicle is less than the current simulation clock time, then space available at the entry section to enter in the road system is checked. If space is available and vehicle also satisfies space

headway criteria at given entrance speed, then the vehicle is assigned to grid elements, which it can occupy. After assignment process the same process is repeated until there is a vehicle on top of the queue whose arrival time is less than the current simulation clock time.
(vi) Scanning of grid elements of the grid road system from right to left and top to bottom is carried out. Direction of search is shown in Figure 3.28. Order of selection of vehicles for decision making will be $A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8, A_9$. Hence, a vehicle which is selected first depends upon its position on the road system.
(vii) If a vehicle is found during scanning of grid elements, then it is checked whether it has reached its destination or not. If it is found that destination flag is True, then grid elements occupied by the vehicle are assigned as NULL and the space is freed. If the destination flag is False then it is necessary to predict the vehicle's next set of coordinates. Firstly left move function is called. In the left move function vehicle takes decision regarding yielding. After checking area rear of the current vehicle, vehicle decides to yield or not depending upon probabilities based on difference in free speed with following vehicle and inter-vehicular lateral spacing required by following vehicle for performing safe overtaking operation. If vehicle decides to yield then x_displacement and y_displacement are calculated and vehicle is assigned to the new calculated position by vehicle assign function. The current grid elements occupied by the vehicle are assigned as NULL.
(viii) **lt_move function:** lt_move function is called in mainmove function. Function calculates left and forward movement of the vehicle and it also assigns the vehicles to new positions in a road system. Previously occupied grid elements are assigned as NULL, and then boolean variables check and flag are assigned as True and False respectively. Macro algorithm of this function is given in section A.2 of appendix A.
(ix) **left_move function:** left move function is called in lt_move function. Function is called in different situations. Mostly this function is called during yielding and left overtaking process. Macro algorithm of left_move function is given in section A.3 of appendix A.

If left move flag is found to be false (i.e., current vehicle is not required to yield) then vehicle will call right move function. In the right move function vehicle decides to overtake front slow moving vehicle from right. After checking the area in front of the current vehicle, vehicle decides to overtake the interacting vehicle which is nearest. Overtaking decision is taken depending upon probabilities based on difference in free speed of current vehicle and overtaken vehicle, and available inter-vehicular lateral spacing present on the right of the overtaken vehicle. If vehicle decides to overtake on the right then x_displacement and y_displacement are calculated and vehicle is assigned to the new calculated position by vehicle assign function. The current position occupied by the vehicle is assigned as NULL.

(x) **rt_move function:** rt_move function is called in mainmove function. Function calculates right and forward movement of the vehicle and it also assigns the vehicles to new position in a road system. Previously occupied grid elements are assigned as NULL, then boolean variables check and flag are assigned as True and False respectively. Macro algorithm of rt_move function is given in section A.4 of appendix A.
(xi) **right_move function:** right_move function is called in rt_move function. Function is called in different situations. Mostly this function is called during overtaking process. Macro algorithm of right_move function is presented in section A.5 of appendix A.

If right move flag is found to be false then the vehicle will call forward move function. In the forward move function a vehicle checks search area lying in front. Vehicles are considered for decision making which are present directly in front of the current vehicle. If vehicle lies in the category in which overtaking can be done from the left side also then decision regarding overtaking from the left direction is taken. Decision for overtaking from the left is taken depending upon difference in free speed of current vehicle and overtaken vehicle and available inter-vehicular lateral spacing present left of the overtaken vehicle. If vehicle decides to overtake from the left then left x_displacement and y_displacement are calculated and vehicle assigned to the new calculated position. The current grid elements occupied by the vehicle are assigned as NULL.

If in forward move function left overtaking flag is found to be false then the vehicle will decide to move in forward direction without moving to left and right. If no vehicle is present in front search area then in this condition it will move as a free flowing vehicle. In the free flowing condition a vehicle can accelerate up to its maximum acceleration capability depending upon power mass ratio in order to attain its free speed. If vehicles are found in the frontal search area then those vehicles are only selected for decision making which are directly present in front of the vehicle. Vehicle which is nearest to the current vehicle is selected for decision making. If sum of the head length and tail length is less than space headway between two interacting vehicles then vehicle is said to be free flowing and if condition is found to be false then vehicle is assumed as constrained.

In constrained situation two methods are adopted for calculating vehicle coordinates in the next time interval. In the first method non-colliding type of car following model is used for calculating vehicle coordinates in the next time interval and in the other method fitted space headway polynomials for different combinations of vehicle group interactions are used for calculating vehicle coordinates in the next time interval. Vehicle is assigned to the new calculated position and current grid elements occupied by the vehicle are assigned as NULL. Similar decisions for other vehicles present on the road system are made.

(xii) **fw_move function:** fw_move function is called in mainmove function. Function calculates forward movement of the vehicle and assigns it to the new position in a road system. Previously occupied grid elements are assigned as NULL, boolean variables check and flag are assigned as True and False respectively. Computer algorithm of fw_move function is given in section A.6 of appendix A.
(xiii) **forward_move function:** forward_move function is called in fw_move function. Function is called in different situations. Mostly this function is called when vehicle is neither performing yielding nor overtaking. Macro algorithm of forward_move function is given in section A.7 of appendix A.
(xiv) After the end of traffic simulation process the statistics of traffic flow parameters is calculated. Vehicle information for statistical analysis is stored. Overtaking operations performed during current simulation time is analysed. At a given time vehicle information for animation programme and other analysis requirement is printed in different files.
(xv) Again for checking road system occupancy, status of the vehicles is scanned. If road system is found to be empty then road_system_empty_flag is assigned as false else road_system_empty_flag is assigned as true. For all the vehicles present in road system time is incremented by Δt.
(xvi) If time is less than end of simulation period or road system empty flag is false then the same process of scanning road grid elements is repeated in order to predict vehicle coordinates; else the traffic simulation process is stopped.

3.13 SUMMARY

Traffic simulation system consists of various component submodels which are assembled into a realistic structure of the system. The heart of the system is the development of traffic simulation model, which simulates the flow of vehicles. Road and traffic submodels are developed to generate the road and traffic input respectively for the simulation model. Study indicates that about 20 vehicle types use the same roadway. These vehicles vary from fast moving car to slow moving push cart, and are present in different proportions. Vehicles are aggregated into eight groups depending upon close resemblance in terms of physical and operational characteristics.

To realistically represent the road system for mixed traffic, the road is represented by a grid pattern. This representation has the capability to quantify lateral displacement by a vehicle and also facilitates modelling various traffic interactions and their action patterns. A grid of one metre square is adopted and upto four vehicles can share this area. Each grid

element have various attributes which are both static and dynamic in nature. Vehicle is defined as an object, consisting of static and dynamic variables. Static variables are input to the simulation model and are generated from stochastic distributions. Dynamic variables change with time and their values depend upon logical decisions taken by the vehicle.

Two different models have been proposed for traffic generation. The first model directly uses field data for traffic generation while the second model attempts to generate generalised traffic in which the attributes are randomised.

Periodic scanning technique has been used along with vehicle pointer referencing system. Vehicle attributes are stored at specified locations and are accessed through pointers by passing the addresses of these storage locations.

Broad categories of flow status for vehicles are free flowing; constrained flowing; and overtaking and yielding. Relationships are established with regard to longitudinal spacing (head length, tail length), inter-vehicular lateral spacing, lateral spacing from fixed objects, and search area. The overall strategy of the traffic interaction model for the vehicle operates as follows:

- Check the status of the vehicle. Depending upon the status of the vehicle, identify the flow logic.
- Check positioning of the vehicle with reference to physical boundaries. Decision depending upon status variables may be modified, if required.
- A certain area on all sides of the vehicle is searched and the status of the vehicles in those areas are identified. The area search in lateral and longitudinal directions be consistent with the various flow logics of the vehicles.
- Do sorting of the vehicles in the search area, and select the interacting vehicles. Obtain attributes required for describing selected traffic flow operation. Attributes are calculated by studying various conditions between current vehicle and interacting vehicles.
- Update the dynamic variables of the vehicle structure and assign vehicle to new position.

The flow process being dynamic, the stream logic for a vehicle will change with time depending upon its position, speed, status with relation to other vehicles. In free flow situation, the vehicle moves at a uniform free speed of the road block. In the constrained flow situations, car following model is used to calculate acceleration rate based on relationship with the leading vehicle. The space headway polynomials derived from the field data are also used to compute minimum space headway between two interacting vehicles. These submodels are used in following unidirectional traffic flow situations:

- Following a slower vehicle;
- Yielding to the left in order to provide space for faster vehicle to perform passing operation.

The overtaking behaviour is represented by probability function. Two probability functions are constructed, one based on difference between free speeds of overtaking and overtaken vehicles (ΔFS) and other based on inter-vehicular lateral spacing (IVLS). The probability of overtaking is the minimum of these two probabilities.

The yielding behaviour of front vehicle is stochastic in nature and is also dependent on the difference between free speed of front and rear vehicles and inter-vehicular lateral spacing between the two vehicles. Two probability functions are formulated and actual yielding probability is determined from them.

Chapter 4

MODEL FOR ANIMATION OF SIMULATED TRAFFIC FLOW

4.1 INTRODUCTION

Computer aided graphics (CAG) leads to the concept of animation. It is well known that graphical displays are considerably more striking and meaningful than printed summary statistics and it is easier for human to manipulate complex information more efficiently in the form of pictorial images. Therefore graphics, and in particular color graphics, provide enhanced visualization of simulation objects; for example, static graphics can be used to support a view of network diagrams and animated graphics to support views of transaction movements in a very good fashion.

In simulation the number of possible alternatives are very large in number and to produce optimum results is difficult and time-consuming. Nelson and Ravindran (1985) suggested that a pictorial representation of variables of interest would be helpful in reducing the number of alternatives to be simulated. Animated graphics is considered to be a highly desirable feature in simulation software and especially in the field of traffic flow simulation. Netsim (Liberman et al., 1977-79) used animation in network traffic flow simulation and it was extremely useful in the validation of network simulation model. Animation can be used to visualise and explain how programmes and algorithms work by creating graphical snapshots and movies correlated with the programme's actions. London and Duisberg (1985) proposed that animation would be extremely useful in programme design, development, and debugging.

The formulated traffic simulation model simulates the flow of twenty different vehicle

types of motorised and non-motorised vehicles. The model system consists of various components submodels. The flow logic of the vehicle at an instant is decided by a decision process considering interactions in close vicinity. The decision process of overtaking, yielding also involve probabilistic functions. The model outputs include longitudinal and lateral positions, speed, acceleration/deceleration, flow status (free, constrained, overtaking, yielding etc.) at uniform time interval. The output could be used to analyse the performance statistics of the individual vehicles and also of the traffic system. This analysis could be helpful in calibrating the model parameters, overall validation of the model. Only a fully validated and calibrated model could be used to simulate different roads and traffic conditions. An animation model is developed to understand working of simulation flow logics and to facilitate calibration and validation process.

4.2 OBJECTIVES

The study aims to animate the flow of simulated traffic to have a better understanding of the simulation process. The main objective is to develop programme system that provides animated display of the simulated traffic flow and also graphic display of individual vehicle position, velocity and acceleration along time.

4.3 ANIMATION OF SIMULATED TRAFFIC FLOW

Simulation models are supposed to help the developer to study the structure of the system being simulated and by doing so better understand the system. The user is also supposed to observe the flow process of the model. But the traffic simulation models generally do not provide aids to the user to observe the flow in simulation experiments. The simulation models behave like a "Black Box" to the user and provide the final output. Animation of the simulated traffic flow may be highly informatory to the user and the model developer.

In traffic simulation model, outputs are stored in an event file containing details of all the different types of events encountered during traffic flow. It is very difficult to analyse the movement of simulated vehicles with the help of a event file to visualise the vehicle operations such as yielding, overtaking, meandering etc. As the urban traffic flow is a complex phenomenon hence it requires better understanding of model logic and traffic manoeuvers. This can be achieved in a better way by the graphical display of traffic simulation process which will help the designer to enhance understanding of the logic and make decisions to

speed up the process. In order to understand the same, computer graphics software for animating road traffic flow has been developed in two parts. These are

- Animation programme system
- Graphic display of vehicle trajectories

4.4 ANIMATION PROGRAMME SYSTEM

With a three dimensional viewing facility, it is easier to visualise various traffic operations such as meandering, overtaking, yielding etc. from any camera (observer) position referring to any point in the viewing area. The animation programme system helps in visualising the system as a whole. It helps in bringing salient features of the system to the user view. It also helps in tracing out interactions of each individual vehicle in system.

Animation programme includes event oriented animation and animation at the fixed time intervals. In the event oriented animation, vehicles are moved and displayed at variable time intervals, while in periodic animation simulated vehicles are displayed at fixed time intervals. Animation of traffic has been divided into two types depending upon observer position.

- Animation of traffic flow when observer position is fixed
- Animation of traffic flow when observer is moving

4.4.1 Road Representation

Urban roads consist of different road elements such as road way, pedestrian way, median, kerb, signals, shoulders etc. In graphical displays, it is required to represent each road element in different colour and shape, which helps in realistically representing the urban road system. In the present study, geometric modeling of road elements has been done. Model has a capability of generating road of any length and width along with required features of urban road.

4.4.2 Vehicle Representation

Vehicles in the urban traffic mix have wide variation in dimensions and most of the vehicle types are of different shape. Study indicates that about 20 vehicle types are predominantly present in urban traffic mix. Therefore, it is necessary to differentiate each vehicle type so

that it will be helpful in understanding traffic flow process and vehicle manoeuvers. Vehicle color code has been selected for all the twenty vehicle types, which helps in identifying type of vehicle in an animated traffic. For providing realistic view of simulated vehicles, geometric modelling of all the vehicle components is done. These components are assembled to give a realistic three dimensional view. For example in the case of bicycle modelling of components like wheel, frame, handle, seat etc. is required. Most of the vehicle components are represented in term of geometrical shapes like horizontal, vertical, and inclined cylinders, sphere, polygons, spline and b-spline surfaces etc.

For a given vehicle type, its dimensions and colour are fixed. But its position changes with time depending upon logical decisions taken. Due to this, vehicles are drawn with reference to some point in space, which can be taken as centre of vehicle. For animated displays at an instant of time, vehicles present in the system are drawn by passing its centre position and type.

4.4.3 Viewing of Images

Three dimensional vision of simulated traffic from any observer position helps to demonstrate complex traffic flow process. View_Camera graphics routine helps in three dimensional viewing from any position in the space. Attributes required to describe view camera are shown in Figure 4.1 and Table 4.1 gives details of various parameters required to invoke the routine. Boundaries of viewing area are demarcated by fixing the positions of front and back clipping planes. It is also possible to get two type of views (projection) - perspective and parallel. Front and side views, plan and other type of views are obtained by suitably choosing the value of different parameters of camera routine.

4.4.4 Animation of Traffic Flow when Observer Position is Fixed

This programme displays on screen the movement of vehicles as per the simulation programme output. The traffic output file is first fed to a conversion programme which gives an output file, giving the details of vehicle such as identity number, vehicle type, lateral and longitudinal positions, velocity and acceleration etc. This output file is given as input to the animation programme. This programme displays road geometry which includes roadway, shoulder, pedestrian way and median etc. along with traffic movement.

The programme facilitates the user in viewing the desired part of the road stretch in a desired number of windows (view_ports) for different positions of observer. The various input required for displaying three dimensional view are shown in Figure 4.2, the programme cal-

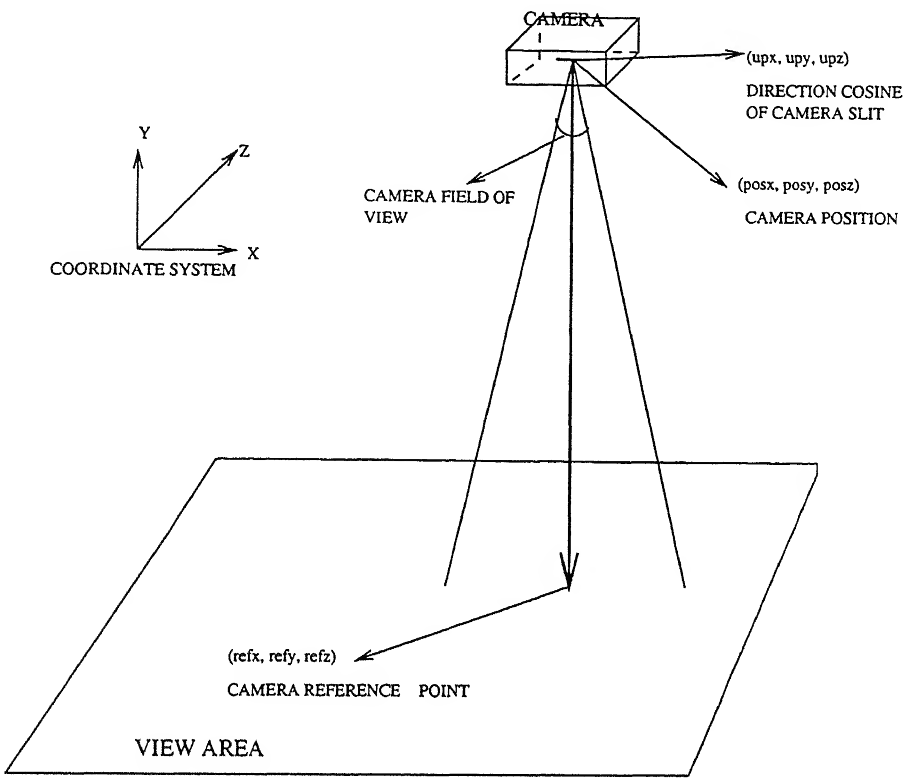


Figure 4.1: Details of View_Camera Starbase Graphics Routine

Table 4.1: Details of View_Camera Starbase Graphics Routine

Variable Name	Variable Type	Description
posx, posy, posz	float	camera position x, y and z coordinates
refx, refy, refz	float	camera reference x, y and z coordinates
upx, upy, upz	float	camera direction cosines along x, y and z directions
projection	integer	Perspective and Parallel
front	float	position of front clipping plane
back	float	position of back clipping plane
field_of_view	float	camera field of view

culates the necessary transformation constant to scale down the road stretch to the graphics screen. Simulation clock time, road details and other features can also be viewed into the separate windows along with animated traffic..

A special feature of the programme system, facilitates viewing animated traffic flow in as many as 32 windows. Basic idea of multi-windowing system is to provide a better feel to the observer, and this can be achieved by viewing same animated traffic flow from different camera positions. Flow chart for traffic animation programme when observer position fixed is shown in Figure 4.3.

4.4.5 Animation of Traffic Flow when Observer is Moving

Concept of moving observer viewing (flying through animation) is used for the first time in this study for animating urban heterogeneous traffic. This concept was earlier introduced in displaying architectural drawing and model presentation and it was also used in robotics to simulate the behaviour of robots.

In the present study, Starbase Graphics (Hewlett Packard, 1991) Camera routine is used as a moving observer, where position of observer is taken as the position of camera and observer reference point is the same as camera reference.

This programme displays the graphical output on screen by using same input in the static observer animation. The programme gives the three dimensional animated view of the traffic when observer is moving in the traffic stream. Simulation clock time, road details and other related vehicle and traffic features can also be seen. In the present study there is a facility to fix observer on a vehicle, and it gives the feel of what driver perceives when he is driving. Advantage of flying through simulation is to understand the various decisions taken by a driver when he is driving in the traffic stream and better way to check various decision logic modelled in the programme. Flow chart for traffic flow animation programme when observer is moving is shown in Figure 4.4.

4.5 GRAPHIC DISPLAY OF VEHICLE TRAJECTORIES

A graphic programme is developed in Starbase graphics to draw time-space, time-velocity and time-acceleration diagrams. The programme divides the viewing surface into four windows, on one window to the left side, road geometry of the current viewing stretch is displayed. In the other window a plot is made by taking time on x-axis and length of the road on y-axis. The programme allows the viewer to view a constant length and time interval. Movement

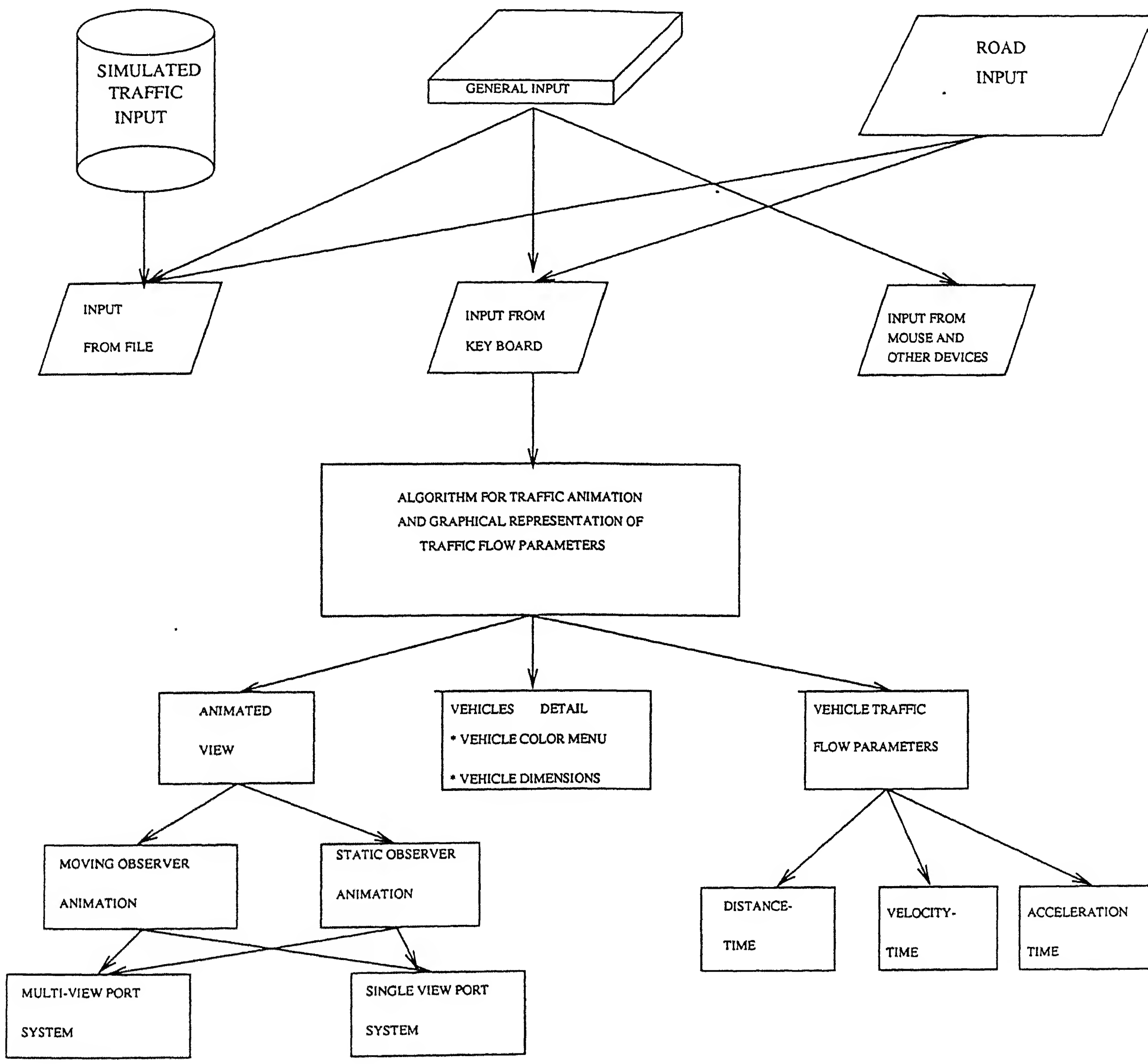


Figure 4.2: Overview of Graphical Package

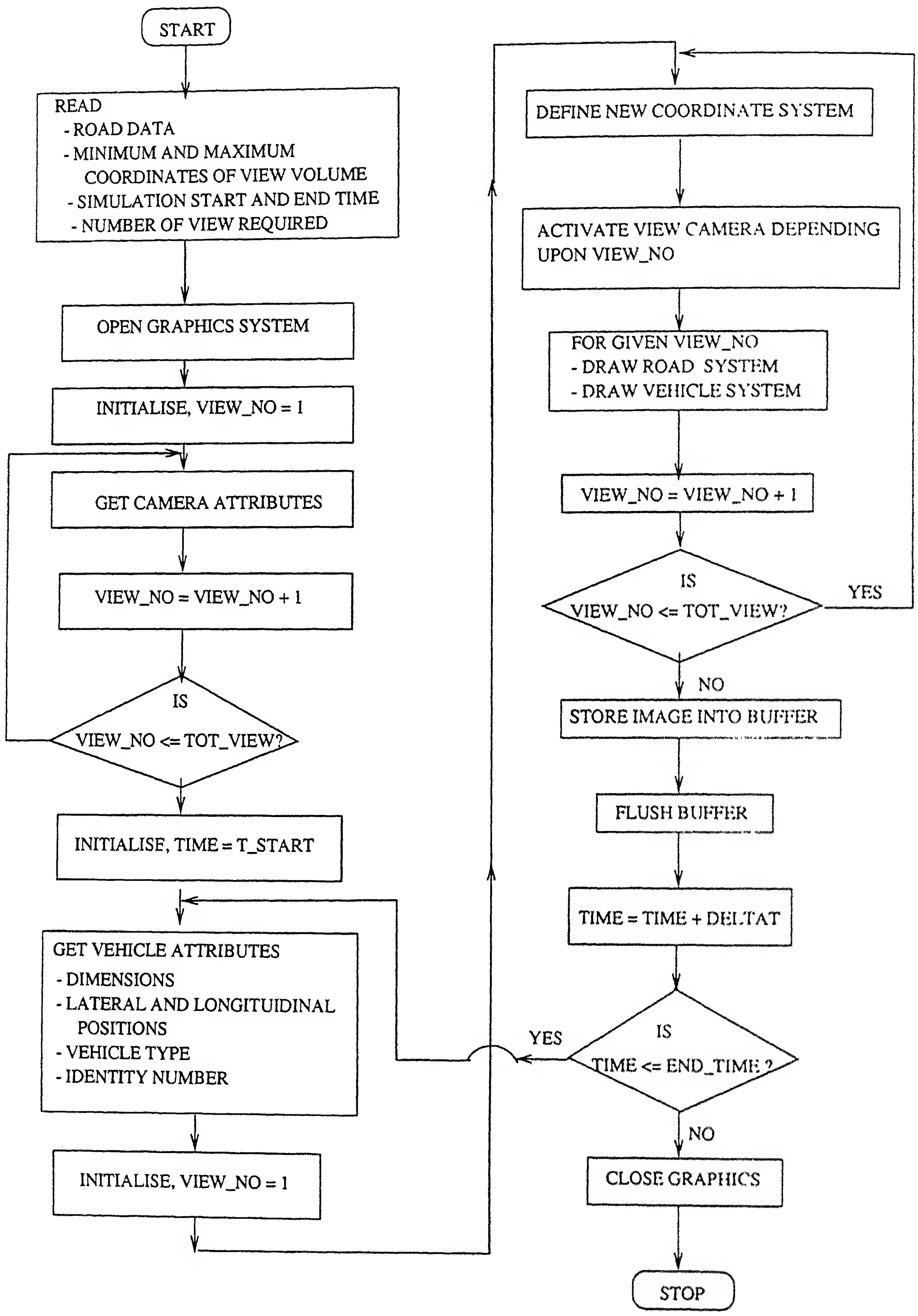


Figure 4.3: Flow Chart for Traffic Flow Animation Programme when Observer Position is Fixed

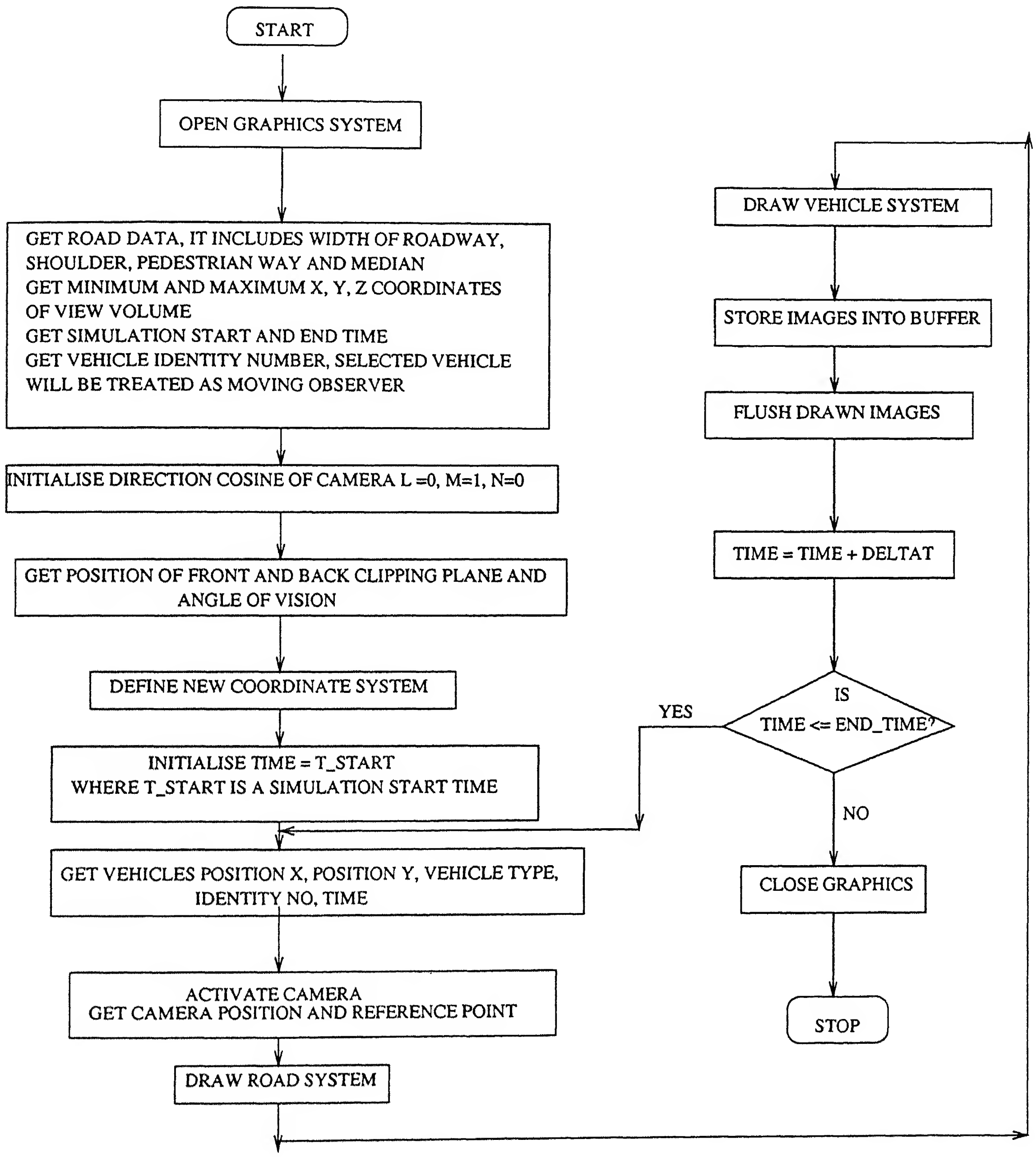


Figure 4.4: Flow Chart for Traffic Flow Animation Programme when Observer is Moving

of vehicles can also be seen on the road on two other windows placed at the bottom, one for time-velocity and other for time-acceleration. Various time features like current time, start time and end time are displayed in the small window at the left most top corner of viewing area.

Programme for graphical display helps in understanding the behaviour of traffic through out the simulation run. Model is also helpful in checking the validity of decision logic of the components of the main simulation model. It also provides a better understanding of acceleration and deceleration capability of different vehicle types in the simulation run. Flow chart for displaying vehicle trajectories is shown in Figure 4.5.

4.6 PACKAGE FOR ANIMATION OF TRAFFIC

4.6.1 Overview

The graphical software package is developed using the graphic Hewlett Packard work stations. Software package is written in C programming language and other details are mentioned in Table 4.2. Graphic software package is developed and coded in modular fashion, so that it is easier to include new graphical subroutines also. The programme coded in C language, is easily portable on most of the graphics system having Starbase Graphics library. Flow chart showing over view of graphical package is given in Figure 4.2.

Macro algorithm of main graphics simulation model is given in sectionB.1 of Appendix B. Animation software is made up of a large number of subroutines, but it is not possible to describe the micro algorithm of all these subroutine. Listing of subroutines used for graphical system is given in Section B.2 of Appendix B.

Table 4.2: Details of software package

Programming Language	C
Working Environment	UNIX
Input Device	Key Board, Button Box, Mouse, Knob Box
Output Device	H.P.Line Printer, H.P.Pen Plotter, Paint Jet, H.P.Laser Printer
Graphics Library	Starbase Graphics Library
Windowing System	X11 Window

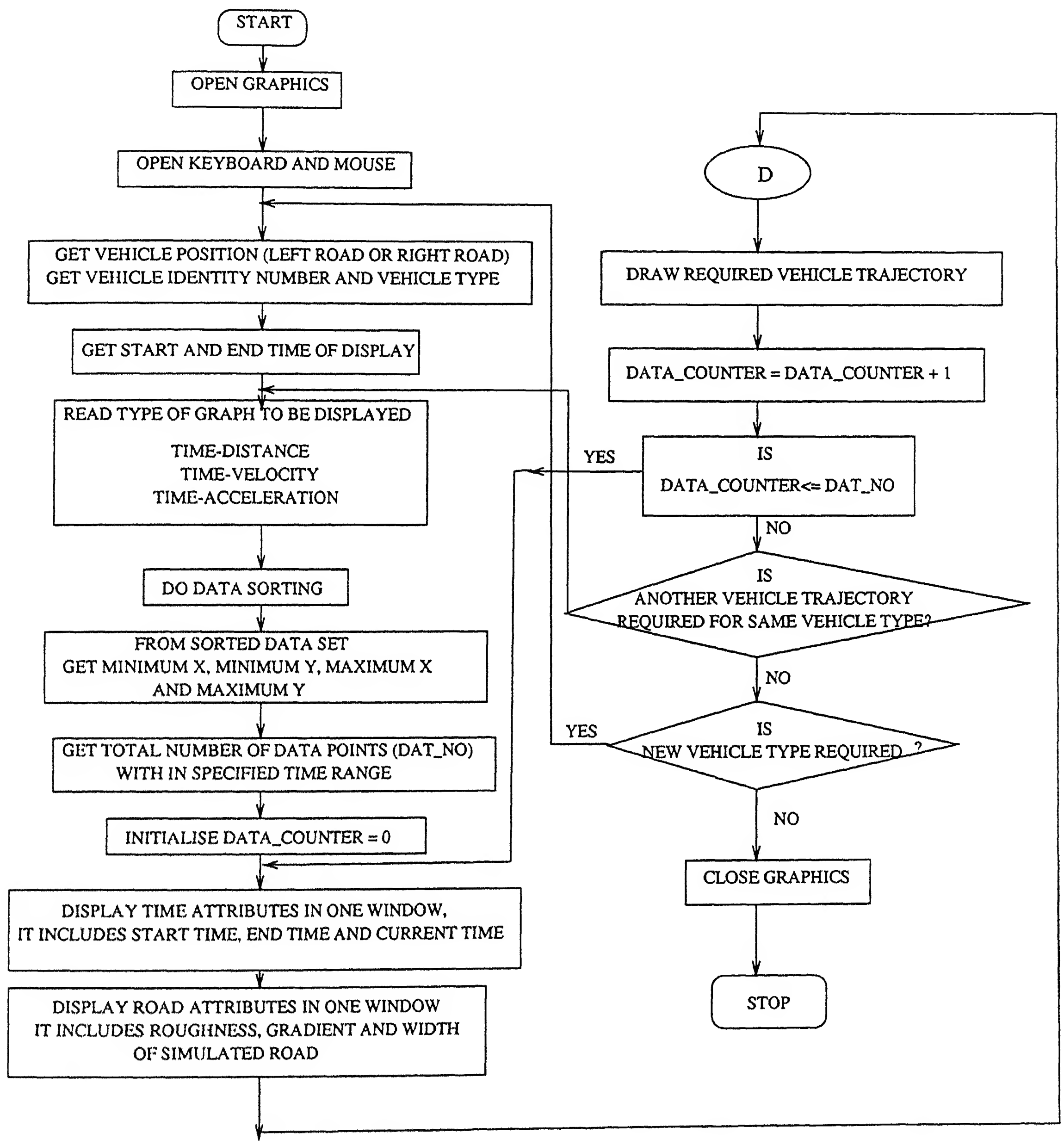


Figure 4.5: Flow Chart for Displaying Vehicle Trajectories

4.6.2 Salient Features of Graphical Package

The salient features of the developed graphical package are:

- Menu driven user-friendly software package.
- Three dimensional view can be seen at any position of the camera and it can be seen in any viewing mode such as parallel view, perspective view.
- Range check for inputs.
- Zooming facility for any type of drawing or view.
- Light sources are fixed at vehicle head lights.
- Front and side views and plan of animated traffic.
- Tables and graphs of various statistics.
- Facility of generating output file for printer/plotter.
- All drawings are sufficiently detailed.
- Various road and traffic elements are represented by different colors.
- Animation of traffic is done in two and three dimensions with high resolution.
- Any position of camera can be fixed in space. It facilitates in seeing any area of simulated road.

Model gives animated view of simulated traffic in different ways. Animated view of traffic helps in checking model logics used for describing vehicle manoeuvers, correlating simulated data with real life data. It gives a feel that model is replicating real life traffic operation. Graphical model gives vehicle trajectories during simulation. Sample graphical displays of the programme system are shown in Figures 4.6 to 4.17.

4.6.3 Applications

Graphic display system package is application oriented and can be used as follows

- To watch the simulated traffic flow on the screen from any observer position.
- To help the developer in understanding and modifying the logic of the model.
- To facilitate the calibration and validation of simulation model.

- Guiding the viewer in identifying the problem areas in the traffic environment, quantifying their extent and analyzing the underlying cause-and-effect relationship.
- In observing and understanding the formation and movement of platoons.
- To demonstrate the complex overtaking phenomenon.
- To comprehend the vehicular interactions for different road and traffic characteristics.

4.7 SUMMARY

Animation can be used to visualise and explain how programmes and algorithms work by displaying animated view of simulated traffic. Animation is also useful in programme design, development and debugging. The main objective is to develop programme that provides animated display of the simulated traffic flow and also graphic display of individual vehicle position, velocity, and acceleration along time.

Graphical model is written in C programming language by using Starbase Graphics subroutines. With a three dimensional viewing facility in Starbase Graphics, it is easier to visualise various traffic operations and action patterns such as meandering. overtaking/passing etc. from any observer (camera) position referring to any point in the viewing area. In this study, periodic (fixed time interval) animation is adopted, which is further divided into two types depending upon observer position and this is classified as:

- Animation of traffic flow when observer position is fixed (Static Observer Animation) and
- Animation of traffic flow when observer is moving (Flying through Animation)

Developed system of graphical models help in understanding the working of the simulation model logics and to validate the programme system of the component sub-models.

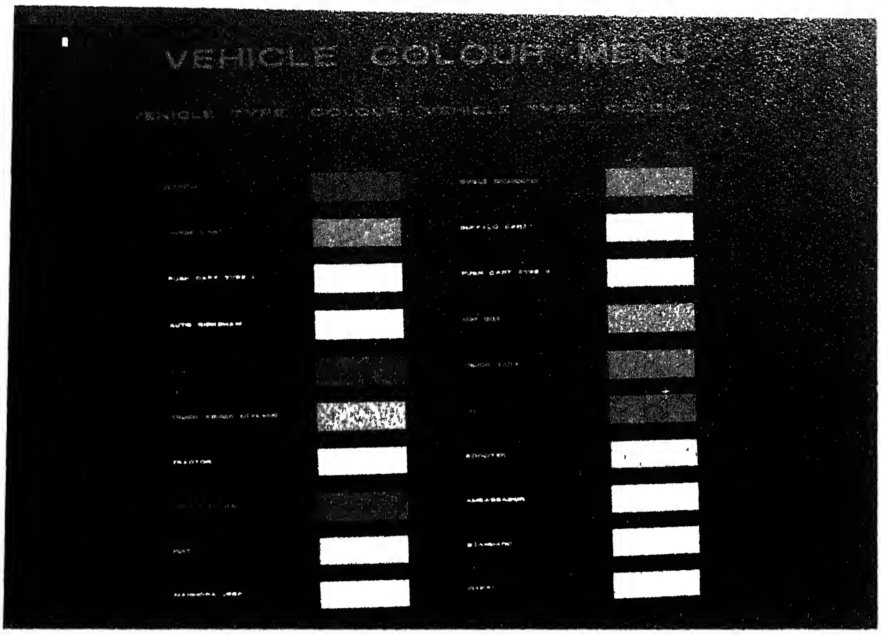


Figure 4.6: Vehicle Colour Code

4.7: Front Animated View of Simulated Traffic (Observer Position Fixed)

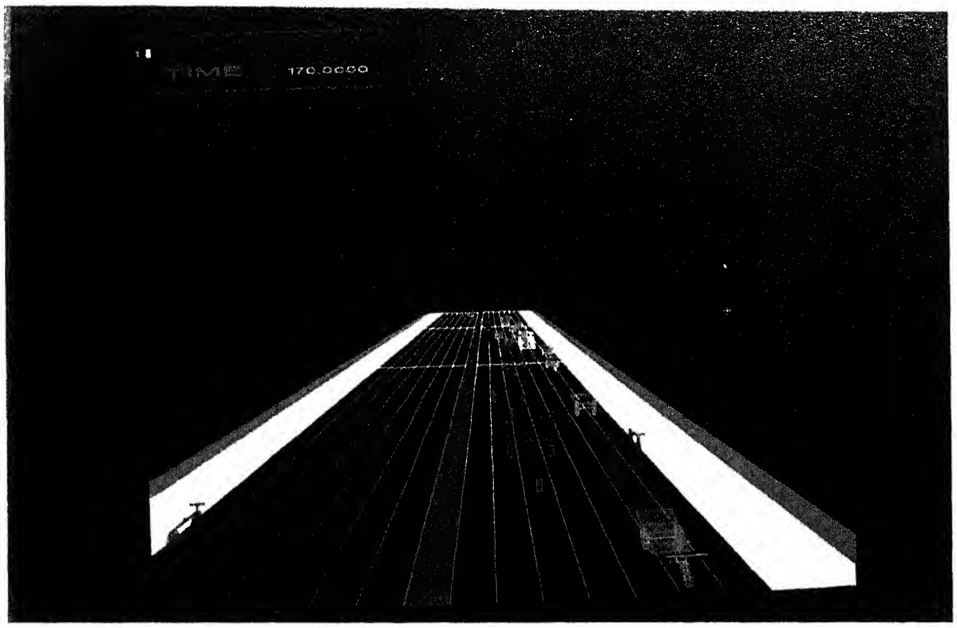


Figure 4.8: Front Animated View of Simulated Traffic (Observer Position Fixed)

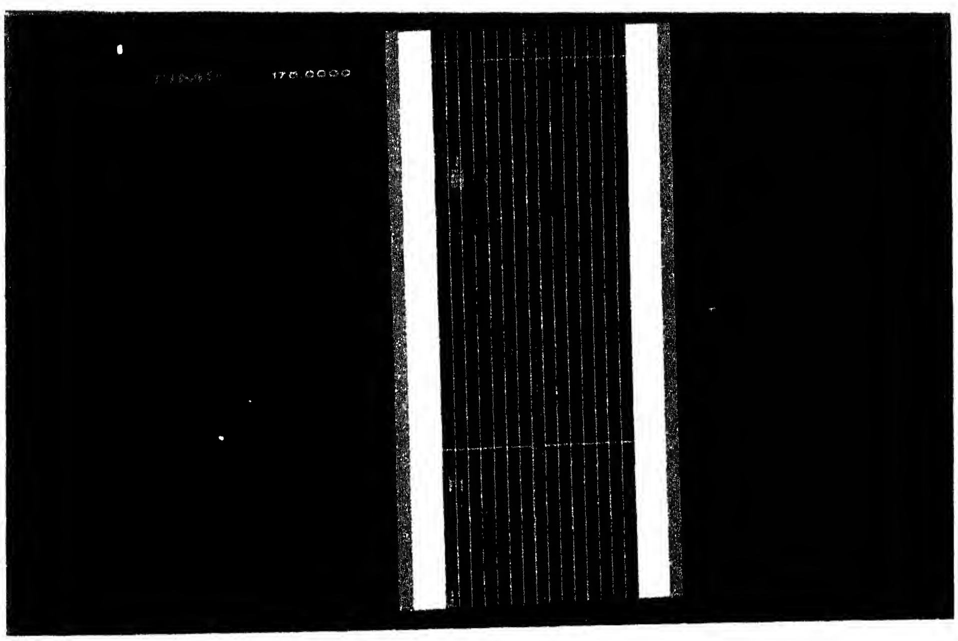


Figure 4.9: Top Animated View of Simulated Traffic (Observer Position Fixed)

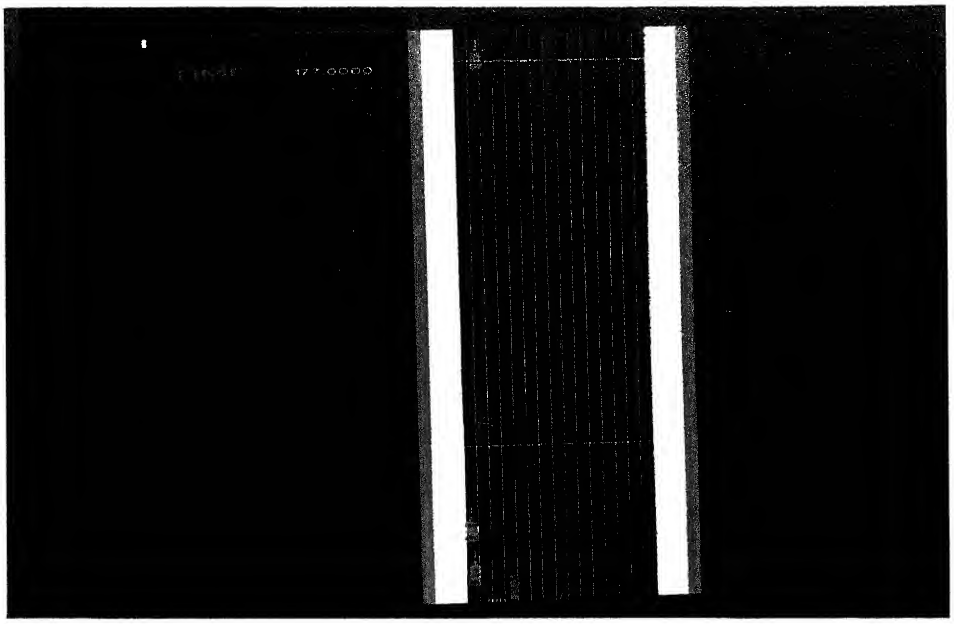


Figure 4.10: Top Animated View of Simulated Traffic (Observer Position Fixed)

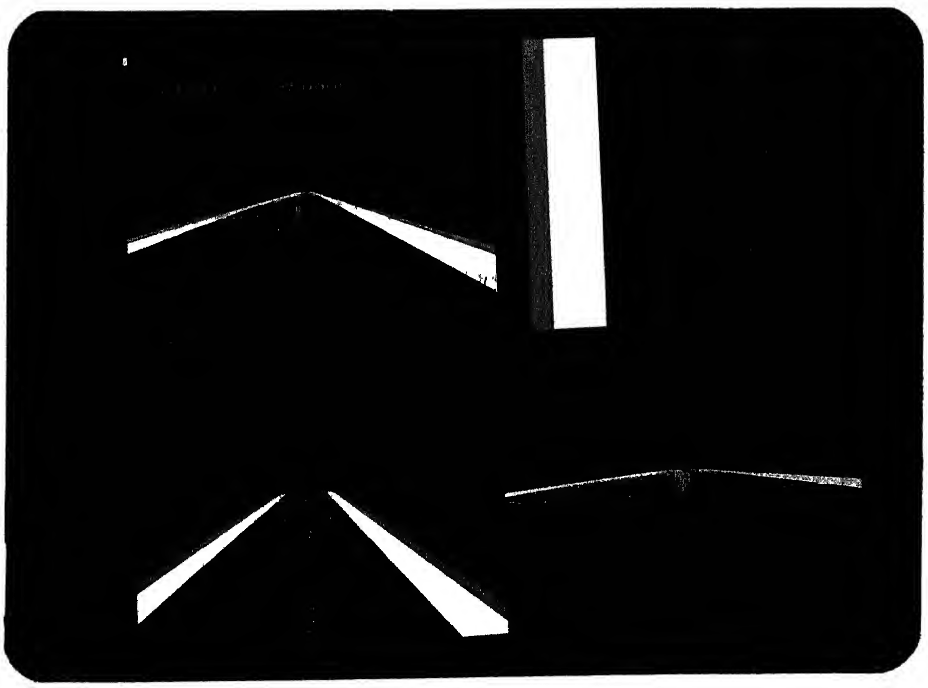


Figure 4.11: View of simulated Traffic shown in Four View Ports (Observer Position Fixed)

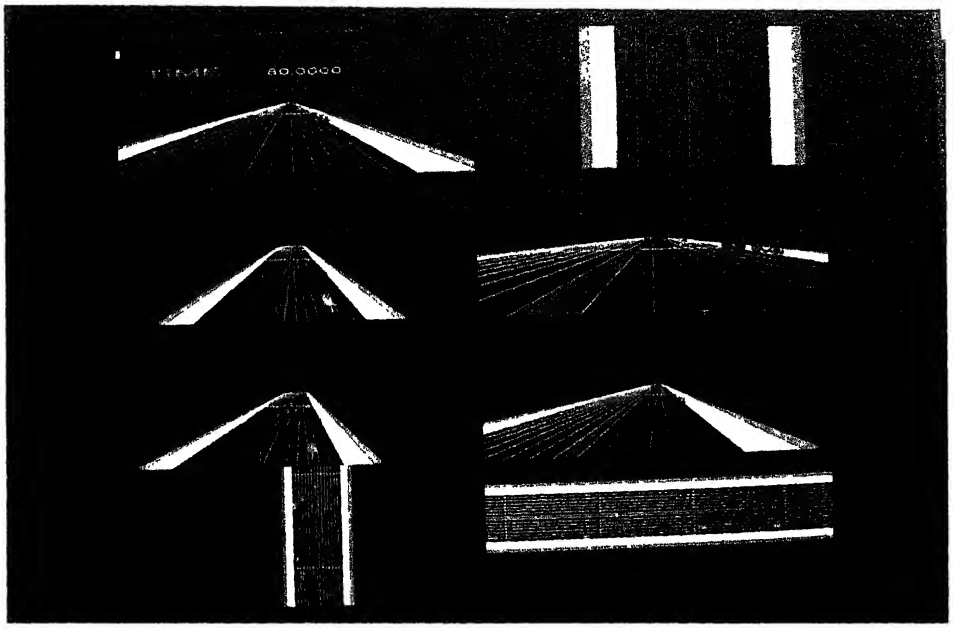


Figure 4.12: View of simulated Traffic shown in Eight View Ports (Observer Position Fixed)

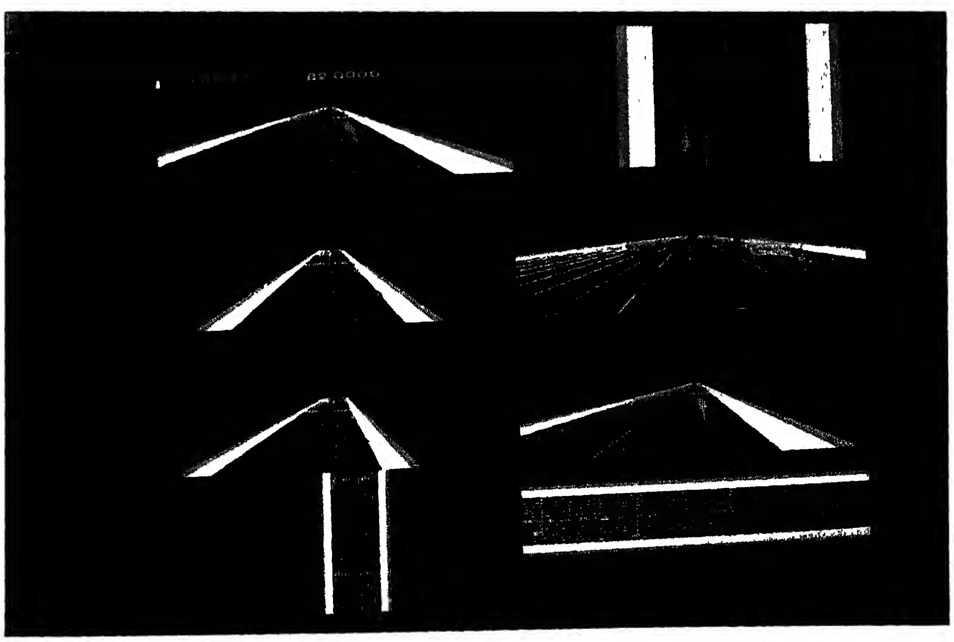


Figure 4.13: View of simulated Traffic shown in Eight View Ports (Observer Position Fixed)

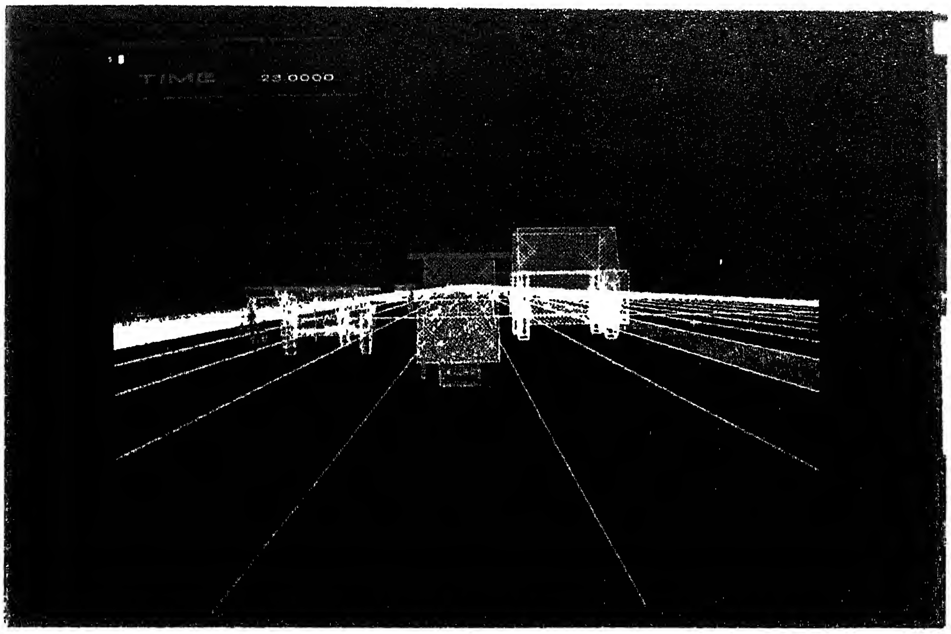


Figure 4.14: Front Animated View of Simulated Traffic (Moving Observer Animation)

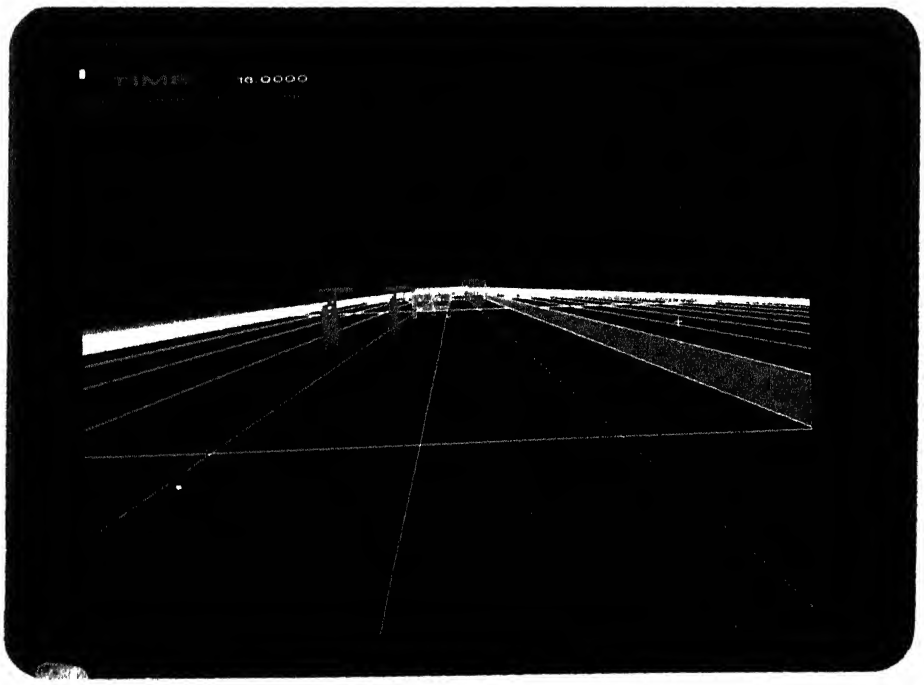


Figure 4.15: Front Animated View of Simulated Traffic (Moving Observer Animation)

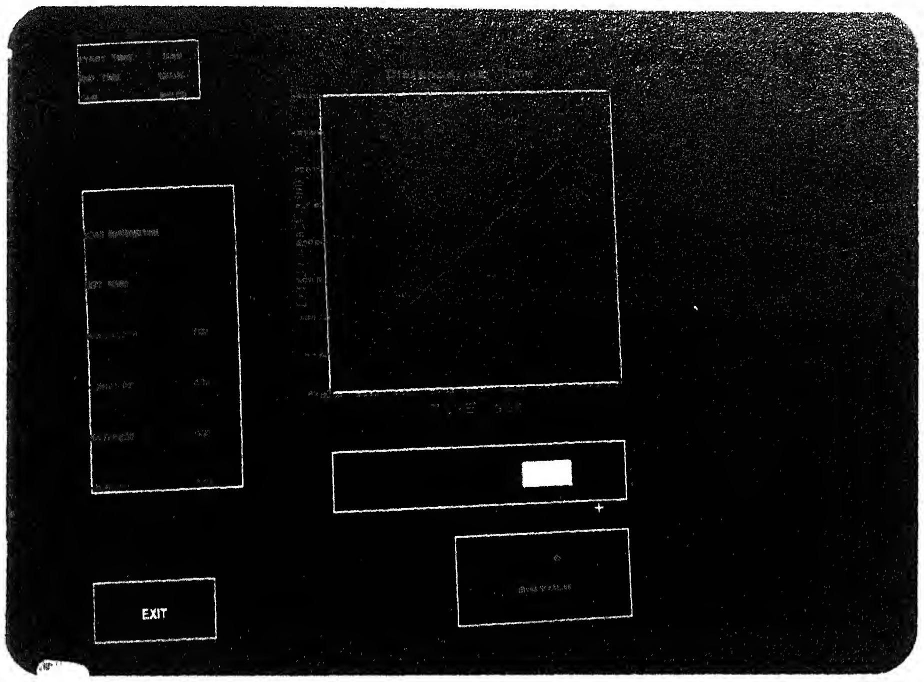


Figure 4.16: Distance vs. Time Graph of Vehicle Type Bicycle

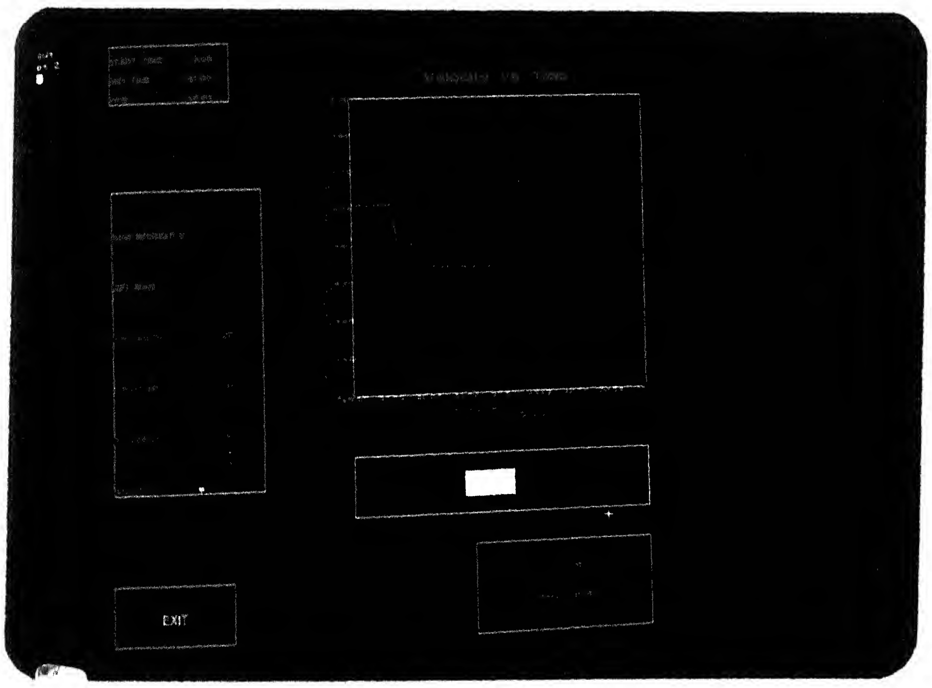


Figure 4.17: Velocity vs. Time Graph of Vehicle Type Bicycle

Chapter 5

TRAFFIC STUDIES FOR SIMULATION MODEL

5.1 DATA REQUIREMENTS

Appropriate and adequate field data and observations are a pre-requisite for successful simulation modelling. Such data are essential for the following phases of model development:

- Formulation of an accurate flow logic system to enable structuring an appropriate model.
- Calibration of the logic based model and components submodels.
- Validation of the calibrated models.

For successful development of the Simulation Model for heterogeneous urban traffic as formulated in the Chapter 3, the data required for various phases are given below:

- **Free Speed Study** - Speed of free flowing vehicles.
- **Time Headway Study** - Identification, vehicle type and entry time of vehicles to the road section.
- **Space Headway Study for Constrained Flow** - Spot speed of interacting vehicles and spacing maintained by following vehicles.
- **Lateral Space Study (Overtaking/Yielding Manoeuvers)** - Spot speed of interacting vehicles (Overtaking and Overtaken Vehicles) and lateral spacing between them.

- **Lateral Space Study for Vehicles from Physical Barriers, i.e., Median, Pedestrian Way** - Spot speed of vehicles and lateral spacing of vehicles from physical barriers.
- **Calibration/Validation of Model** -
  - Vehicle characteristics at entry e.g. type, spot speed, lateral position and entry time.
  - Vehicle characteristics at exit e.g. type, spot speed, lateral positions and exit time.

Data requirements and methodology adopted for collecting the data for various phases of study are elaborated in Figure 5.1. Application of the data in the development of component models of the simulation system along with data needs for successful calibration and validation of the simulation model are also shown in Figure 5.1.

5.2 CHOICE OF DATA COLLECTION SITES

As the model aims to realistically simulate the flow of heavy heterogeneous traffic on Indian urban roads, it is planned to collect data on a major arterial of the Kanpur city. The selected road (Medical College - Benajhabar - Mall Road) has the characteristics of typical urban arterial roads in Indian cities. It is four lane wide with centrally raised median. On various sections of this road, traffic volume is of the order of 1600-3000 vph during peak periods.

Two sites on the selected road are identified for data recordings. These sites are:
Site I (Medical College - Bena Jhabar) - For free speed study only by radar speedometer.
Site II (Parade - Barachauraha) - Traffic flow studies on road stretch by video recording.
Figure 5.2 and Figure 5.3 shows the locational and other features of these two sites. Table 5.1 gives the various characteristics of these sites.

5.3 METHODOLOGY FOR FIELD STUDIES

5.3.1 Free Speed Studies

Free speed of motorised vehicles are recorded by Radar speedometer located at three different locations of Site I road section. All the instruments were located as inconspicuously as possible so that their presence would not influence the speed of drivers. Radar speedometers give the spot speed of vehicles. These measurements are recorded only for those vehicles which appear to be moving at their free speeds. This occurs when there is sufficient headway

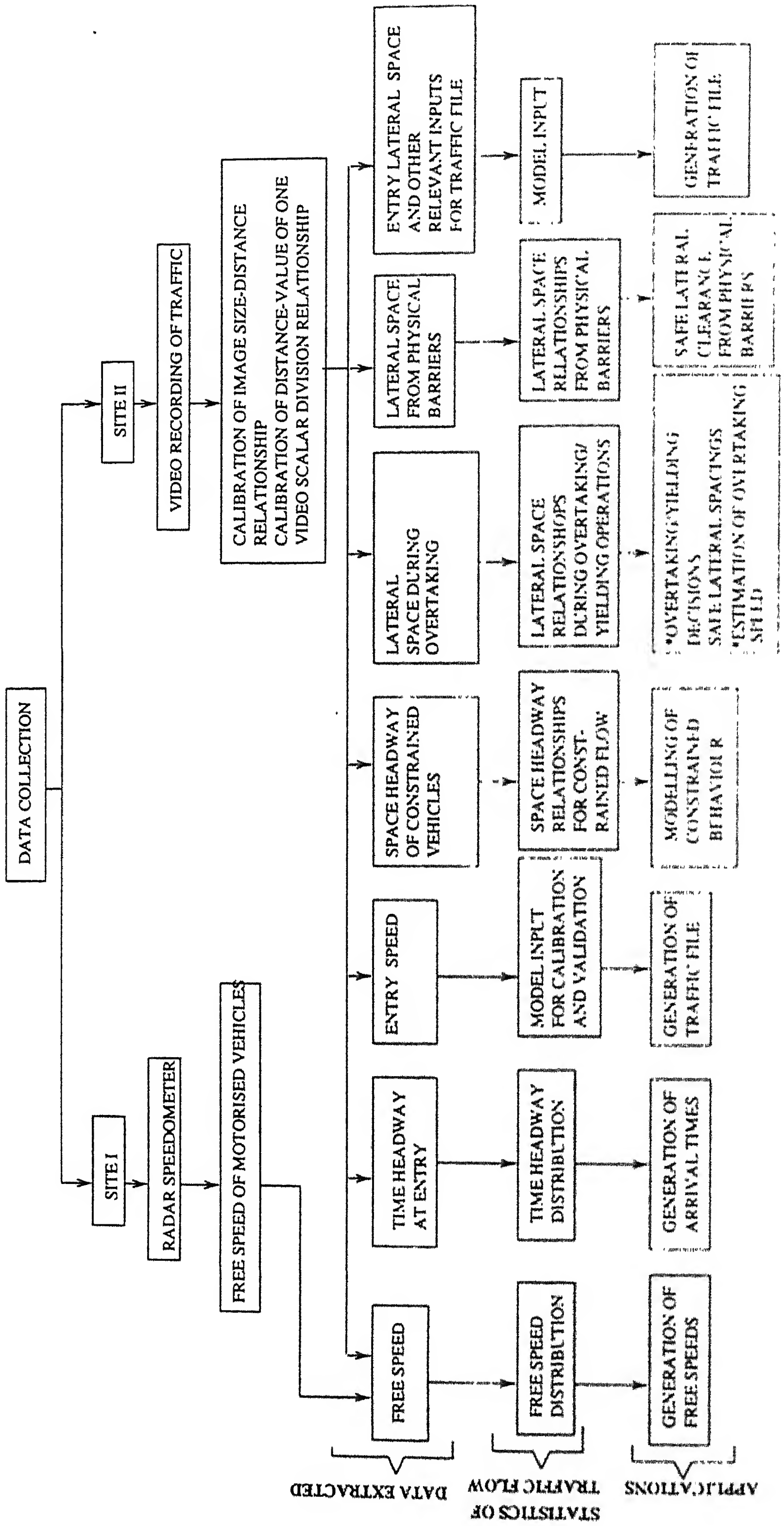


Figure 5.1: Field Studies for the Simulation Model

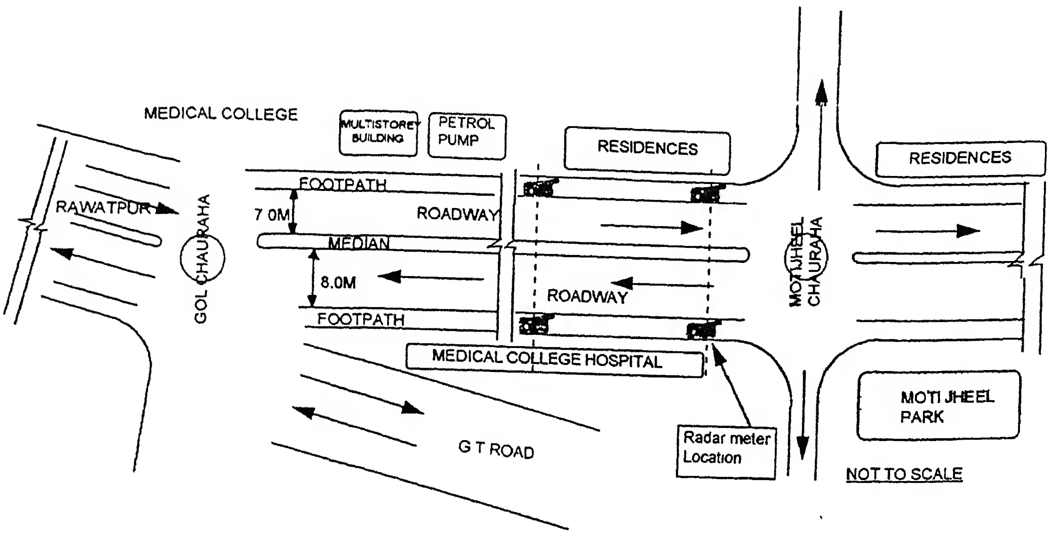


Figure 5.2: Plan for Site I

Table 5.1: Details of Sites Selected for Free Speed Study

Road Characteristics	Site I	Site II
Road	Medical-Benajhabar-Mall Road	Medical-Benajhabar-Mall Road
Location	Near Medical College	Near Ursala Hospital between Parade - Barachauraha
Type of Flow	Moderate to Heavy	Heavy to Very Heavy
Road Width	Two Lane in each Direction	Two Lane in each Direction

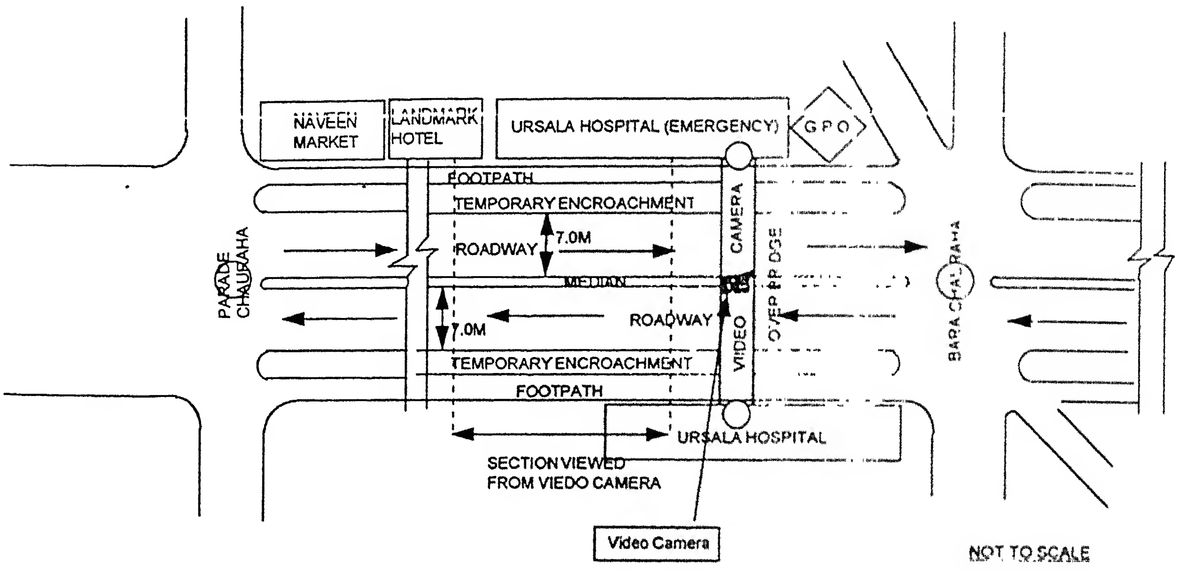


Figure 5.3: Plan for Site II

for the vehicle and there are no interacting vehicles near by. Free speeds are generally observed when volume is low, i.e., in off peak periods. Recording was done for 16 hours on two days.

In order to check correctness of the reading obtained by the radar speedometers, a survey was conducted in which the speed of the same vehicle was recorded simultaneously by two radar speedometers. The readings are compared statistically and it was found that there is no significant difference between these.

To check the accuracy of the radar speedometer, observations are also made by running vehicle at known speeds. These experimental observations tested the accuracy of radar speedometer readings.

Slow-moving vehicles such as bicycles and cycle rickshaws are not amenable for speed measurement using radar speedometers. These vehicles do not reflect the waves back to the instrument due to openings in wheels. The same is the case for motorised two wheelers. Therefore, it is necessary to employ video image processing technique for free speed measurements of non-motorised vehicles and motorised two wheelers.

5.3.2 Traffic Flow Process Studies

Detailed information of traffic flow process can be obtained from the following studies:

- Time headway study
- Space headway study for constrained flow
- Lateral space study for overtaking and yielding manoeuvers
- Lateral space study for physical barriers
- Study for calibration and validation process

The observations for these studies are to be made on a road stretch which may be simulated. It is planned to have a video recording of the traffic flow to extract the data for different studies. Video recording of the traffic flow was made from an elevated position of the camera (Pedestrian Overbridge). This position of the camera gave a complete view for about 500 m length of the road stretch in both directions of traffic.

Video recording of the traffic flow was done for a seven hour duration. This duration covered both peak and off peak periods, with flow varying between 1600-3000 vph in each direction. In all data for about 25000 vehicles were recorded. The video instrumentation system for data recording consists of the following main components:

- Video Camera
- Camera Drive Unit
- Video Cassette Recorder
- Video Monitor
- Video Timer

5.4 DATA EXTRACTION

Data to be obtained for different studies is presented earlier in this chapter. Free speed data for most of the vehicle types is obtained directly by the radar speedometer. For the traffic flow studies, the relevant information is to be extracted from the video recordings. Information for a vehicle relates to its longitudinal and lateral positions at a particular time. Spot speed of the vehicle can be obtained from the longitudinal positions of the vehicle at two closely spaced time intervals. This gives the distance traveled during the time interval.

Information of time is directly obtained from the video recording. But the position of the vehicle, both longitudinal and lateral, is to be determined from the video images of the vehicle.

It is planned to record the image size of the vehicle at appropriate times and then estimate the position of the vehicle. The size of a vehicle image depends upon the vehicle type, its distance from the camera, and size of the monitor. For a particular type of vehicle, the image size is inversely proportional to its distance from the camera.

Placing a vehicle at different distances and recording the video images for these locations, the relationship between video image and distance can be established for a particular monitor. This relationship is linear and image size reduces with distance. This relationship could be well suited when the movement of vehicle is exactly perpendicular to camera and accurate measurement of the video image of vehicle width is possible. In this study image size of the vehicles are recorded using the video scalar. The recorded video image size have following problems generally encountered:

- The movement of the vehicle is not perpendicular to the camera position. This may give an inclined image.
- Due to the background of moving traffic, it may some times be not possible to clearly identify the boundary of vehicle width.
- The camera setting may tilt the vehicle image.
- For narrow vehicles like bicycles and scooters, it is difficult to measure the exact image.

Due to the above mentioned problems, the recorded vehicle image size may not be very accurate. So a detailed calibration of distance-image size relationship is attempted.

5.4.1 Calibration of Image Size vs. Distance Relationship

At sections whose distance from the camera are known, image size of different vehicle types is recorded with the help of a video-scalar and distance vs image size is recorded in chronological order.

Suppose there are m sets of observations of distance and image size for a given vehicle type. Let these values be (y_1, I_1), (y_2, I_2), (y_3, I_3), ..., (y_m, I_m). Then by error minimization principle one can fit nth degree polynomial on recorded data set. Error of fitting can be minimized by increasing the degree of polynomial. However, in the present study polynomials of order one and two are fitted on the recorded data set. It is inferred that fitted polynomial

Table 5.3: Comparison of Fitted and Observed Distances from Camera (Vehicle - Tempo)

Image Size	Observed	Estimated	
		1st Degree Polynomial	2nd Degree Polynomial
Number of Video Scalar Divisions	Distance (m)	Distance (m)	Distance (m)
4.75	37.75	34.26	38.24
5.50	30.33	29.93	30.63
6.00	26.64	27.04	26.10
6.50	22.90	24.15	22.01
7.50	15.48	18.37	15.12
8.75	7.36	11.15	8.95
10.50	5.47	1.04	4.89

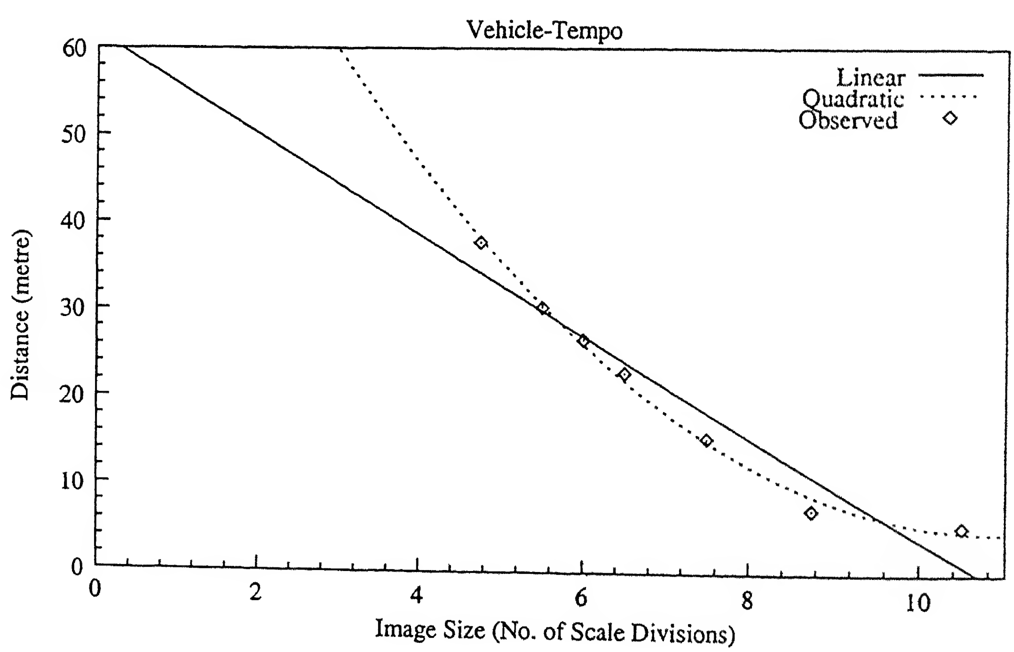


Figure 5.4: Image Size-Distance Polynomial for Tempo

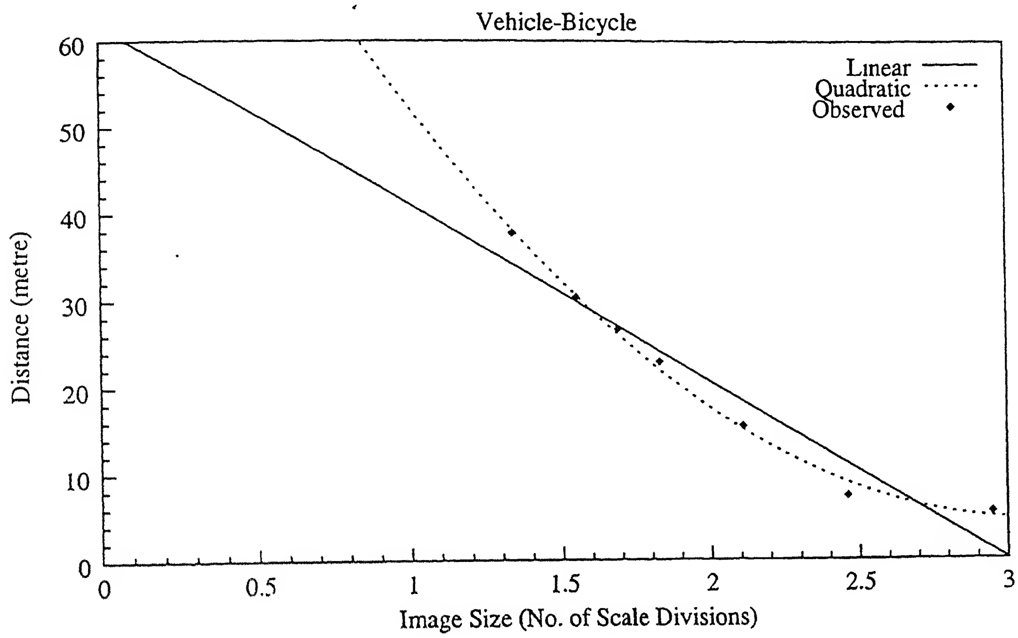


Figure 5.5: Image Size-Distance Polynomial for Bicycle

helps data handling, processing and cross checking the extracted data.

5.5 ANALYSIS OF VIDEO IMAGES TO ACQUIRE DETAILED INFORMATION

5.5.1 Video Image Processing Methods for Spot Speed Calculations

Method I: Observations for spot speed at fixed locations

This is the conventional method in which arrival time of the vehicle at sections, whose coordinates has been already measured in the field, are recorded with the help of video recorded images. It is assumed that the speed is constant over the length of section.

Method II: Observations for spot speed are not at fixed locations

In dense urban traffic situation, it is very difficult to record the precise time of vehicle passing sections of known coordinates and video image size. The situation may arise when

- View of a smaller vehicle is obstructed by the bigger vehicle.
- Vehicle is far away from the camera due to which it is not possible to record exact time at which vehicle is approaching the section.

For spot speed, image size is recorded with corresponding time at two locations and the distance of vehicle from camera is calculated from fitted polynomial (distance-image size). Corresponding spot speed is calculated as ratio of calculated distance and time difference between passing of vehicle at two locations.

5.5.2 Free Speed Study

Free speeds are obtained like spot speed methods for those vehicles that are not interacting and are moving freely.

5.5.3 Time Headway Study

From video data, inter arrival time gaps between the successive vehicles are calculated. This data is decoded for 3.5 hours in each direction of travel. For testing statistical validity of assumed time headway distributions, data was split into six sets, each of one hour duration.

5.5.4 Lateral Space Study

Video Data Decoding for a Lateral Clearance

For interacting vehicles, the lateral spacing depends upon the speed of overtaking and overtaken vehicles. Therefore, it is necessary to decode the data in a such a way that speed of overtaking and overtaken vehicles, and lateral space can be calculated. Two methods have been adopted to extract relevant data from video image.

Calibration of Relation - Distance vs Value of One Video Scalar Division

Video scalar has been used for recording the width of vehicles and other lateral measurements. Size of video image in terms of scalar divisions depends upon the distance of the recorded object from the video camera. Therefore, it is necessary to model the change in image sizes of recorded objects along the length of road. Let there be a set of m observations for value of one video scalar division and distance from the camera. These values are (Vd_1, y_1), (Vd_2, y_2), $(Vd_3, y_3), \ldots\ldots$, (Vd_m, y_m); where Vd_m is the value of one video

scalar division in metres for mth reading and y_m is the distance from the camera where mth reading has been recorded.

$$Vd = a_0 + a_1 y + a_2 y^2 + \ldots\ldots\ldots\ldots + a_n y^n \qquad (5.2)$$

where a_n is a coefficient of nth order term of fitted polynomial.

Analysis indicates that error of fitting can be minimized by increasing the degree of polynomial. But after second order polynomial, decrease in error of fitting is very insignificant. Due to limited number of data points, linear and quadratic polynomials are adopted for calculating lateral spacing. Coefficients of polynomials are given in Table 5.4. Fitted polynomials with observed data points are shown in Figure 5.6. Comparison of observed and fitted values is given in Table 5.5 for first and second degree polynomials. It is also observed that deviations between the observed and fitted values are very small for second order polynomial.

Table 5.4: Coefficients of Distance-Value of One Scalar Division Polynomials

Linear		Quadratic		
a_0	a_1	a_0	a_1	a_2
0.1313	0.00528	0.1394	0.0041	2.7553e-05

Table 5.5: Comparison Between Observed and Estimated Values of One Scalar Division

	Observed	Calculated	
		Linear Polynomial	Quadratic Polynomial
Distance (m)	Value of One Scale Division (m)	Value of One Scale Division (m)	Value of One Scale Division (m)
37.75	0.337	0.331	0.335
30.33	0.291	0.291	0.291
26.64	0.267	0.272	0.270
22.90	0.246	0.252	0.249
15.48	0.213	0.212	0.211
7.36	0.183	0.170	0.172
5.47	0.152	0.160	0.163

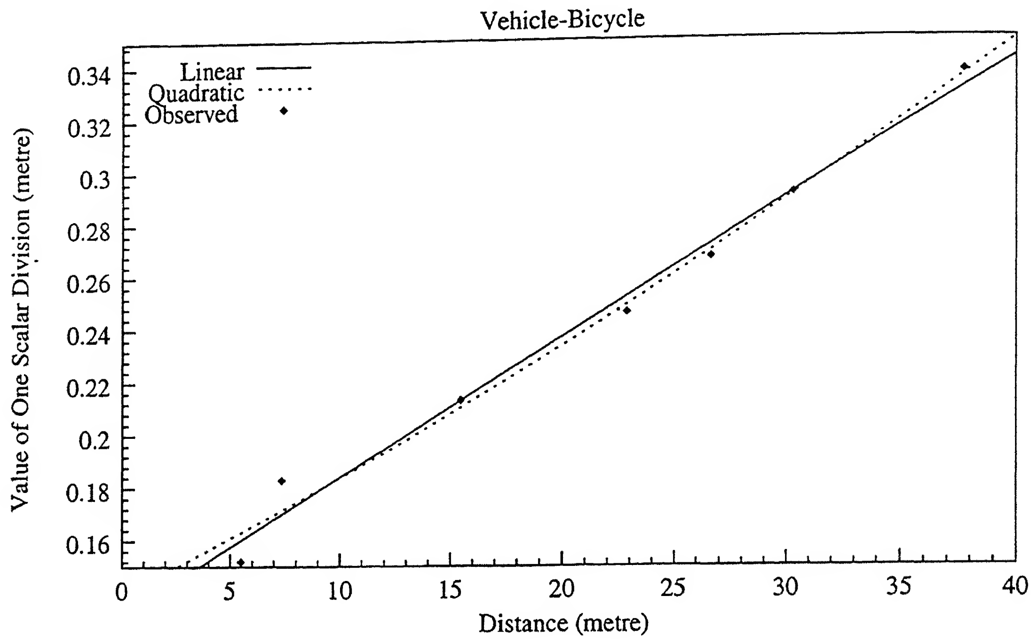


Figure 5.6: Distance-Value of One Video Scalar Division

Method I:- Lateral Space Observations at Fixed Locations

This method is used when it is possible to record the passing of interacting vehicles on at least two fixed locations whose coordinates are known with respect to camera. From the passing times at two locations, the speed of both the interacting vehicles can be determined. It is assumed that both the interacting vehicles travel at uniform speed during the time interval of observations. Distance of recording (d_rec) can be calculated as

$$d\_rec = d + (tim\_rec - v1\_t1) * v1 \quad for \quad tim\_rec \geq v1\_t1, \tag{5.3}$$

$$d\_rec = d - (v1\_t1 - tim\_rec) * v1 \quad for \quad tim\_rec < v1\_t1; \tag{5.4}$$

where d = distance of section from the camera where a vehicle arrives first
v_1 = calculated speed of the vehicle
d_rec = distance of lateral space recording point from the camera
tim_rec = time when lateral space observations are made
$v1\_t1$ = overtaking vehicle arrival time at first section

Reference can be made to Figure 5.7.

Let v_d be the value of one scalar division. Value of one scalar division can be calculated by passing d_rec in equation 5.2. If sp_div are the number of scalar divisions for lateral spacing between two vehicles, then lateral spacing can be calculated as

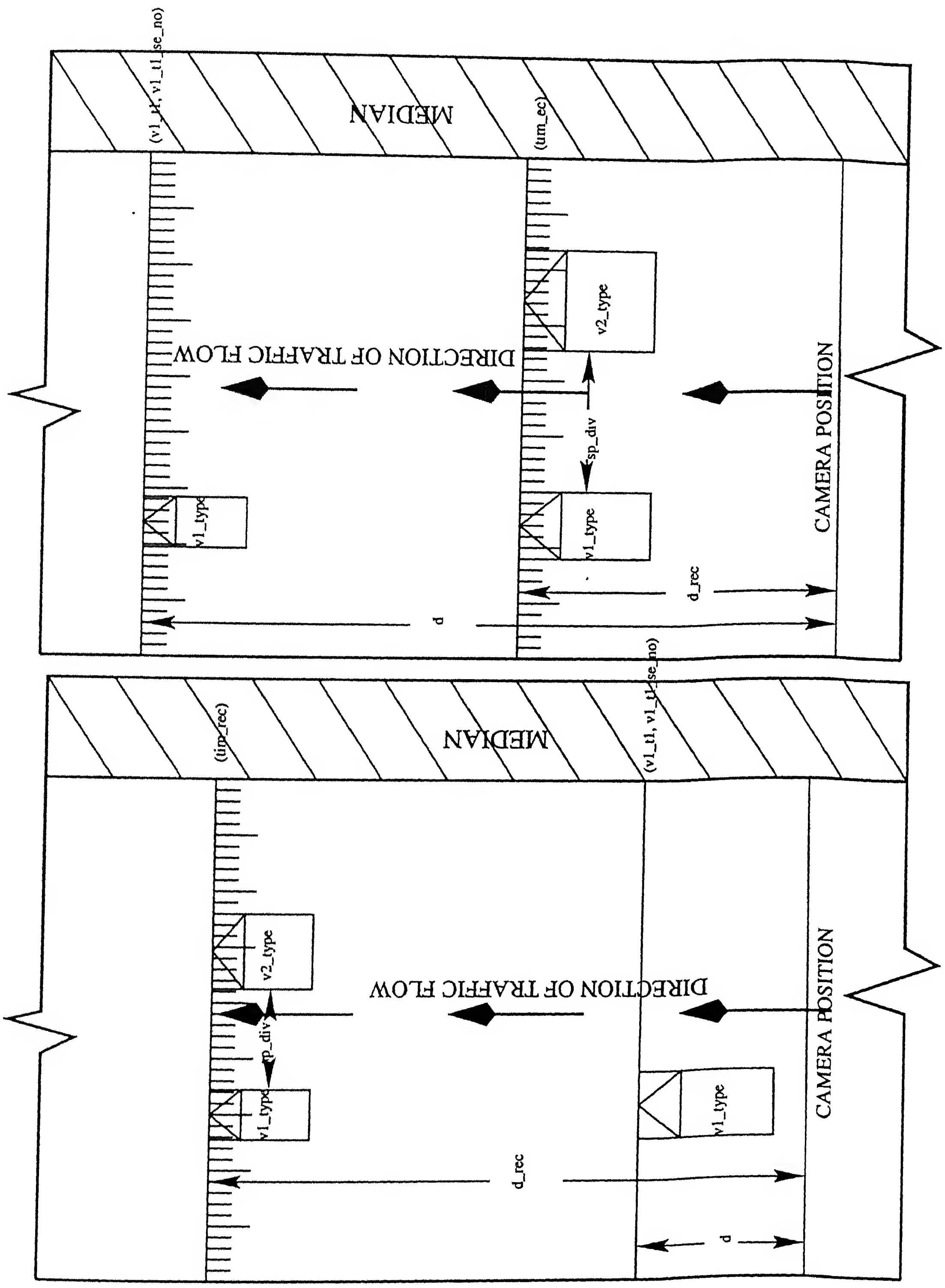


Figure 5.7: a) Positions of Vehicles for Lateral Space Computation by Method I ($time\_rec \geq v1\_t1$) b) Positions of Vehicles for Lateral Space Computation by Method I ($time\_rec < v1\_t1$)

$$\text{lateral spacing} = v\_d * sp\_div \tag{5.5}$$

Method II:- Lateral Space - Observations are not at Fixed Locations

This method is used when it is not possible to record the arrival time of interacting vehicles at some fixed locations. Position of vehicles are estimated at two close spaced times, assuming that speed of both the interacting vehicles remain constant during this period. Distance of point where image size is recorded can be calculated by using the fitted polynomials (Distance vs. Image Size) for different vehicle types. Let

$d1$ = distance of point from the camera where first image reading vehicle type is taken,

$d2$ = distance of point from the camera where second image reading vehicle is taken.

$d1$ and $d2$ can be calculated by passing image size into fitted polynomial for given vehicle type. If polynomial is not fitted for given vehicle type, then transformed image size is used in the polynomial of other vehicle types. If $v1$ is the speed of first vehicle, then $v1$ can be calculated as

$$v1 = \frac{d1 - d2}{v1\_i1\_t1 - v1\_i2\_t2} \quad for \ (d1 \geq d2), \tag{5.6}$$

$$v1 = \frac{d2 - d1}{v1\_i2\_t2 - v1\_i2\_t1} \quad for \ (d1 < d2); \tag{5.7}$$

where v1_i1_t1 = arrival time of overtaking vehicle at first point

v1_i2_t2 = arrival time of overtaking vehicle at second point

Similarly $v2$ can also be calculated for the second vehicle.

Distance of the recording point (d_rec), where lateral spacing is recorded, from the camera can be calculated as

$$d\_rec = d + (tim\_rec - v1\_i1\_t1) * v1 \quad for \ (time\_rec \geq v1\_i1\_t1), \tag{5.8}$$

$$d\_rec = d - (v1\_i1\_t1 - tim\_rec) * v1 \quad for \ (tim\_rec < v1\_i1\_t1); \tag{5.9}$$

After computation of d_rec lateral spacing can be computed as

$$\text{lateral spacing} = v\_d * sp\_div \tag{5.10}$$

where v_d = value of one scalar division

sp_div = number of scalar division for lateral spacing between two vehicles

The positions of the vehicles, required for computation of lateral spacing are shown in Figure 5.8 and Figure 5.9 for the possible different positions of vehicles that can occur during data collection.

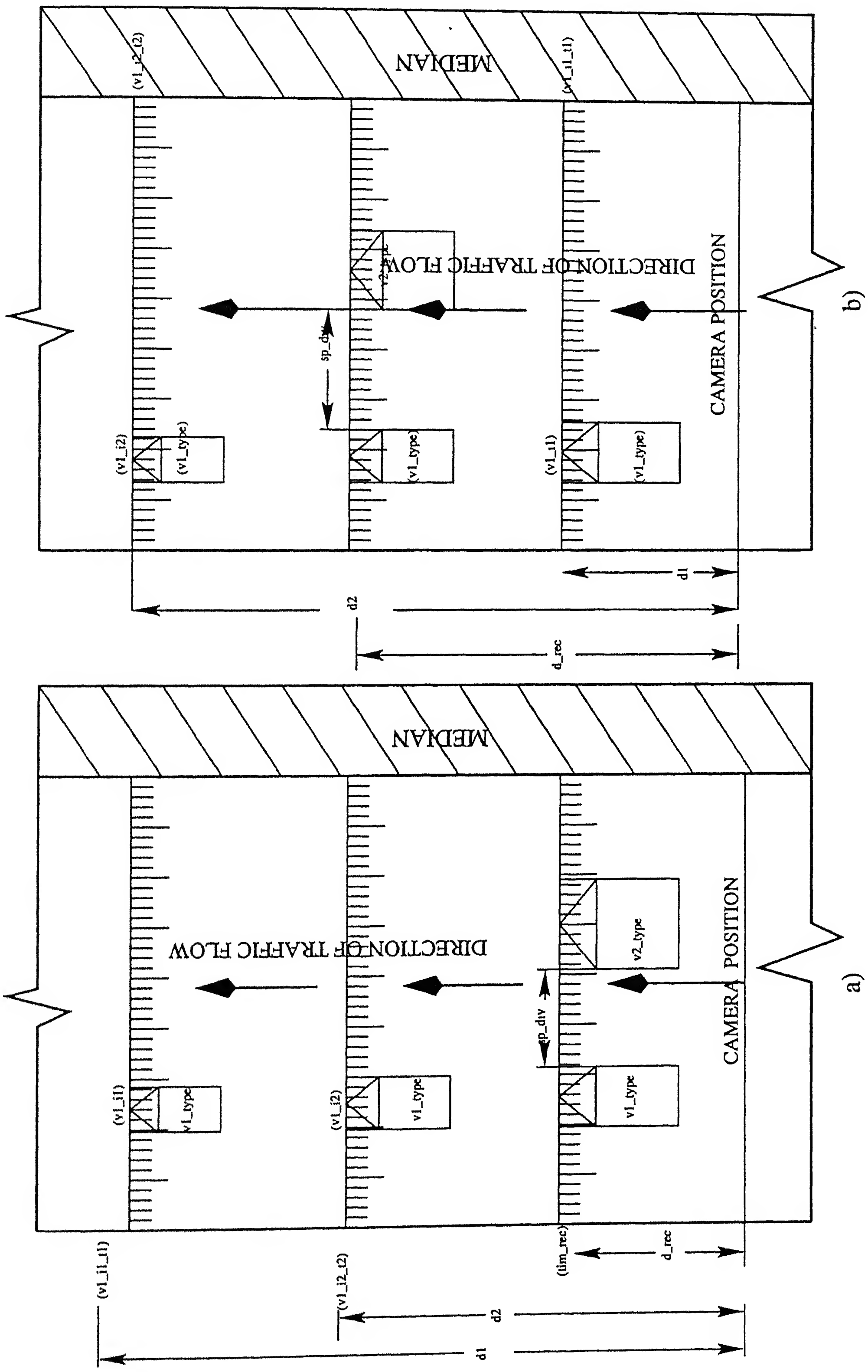


Figure 5.8: a) Positions of Vehicles for Lateral Space Computation by Method II ($d1 \geq d2, tim\_rec < v1\_i1\_t1$) b) Positions of Vehicles for Lateral Space Computation by Method II ($d1 < d2, tim\_rec \geq v1\_i1\_t1$)

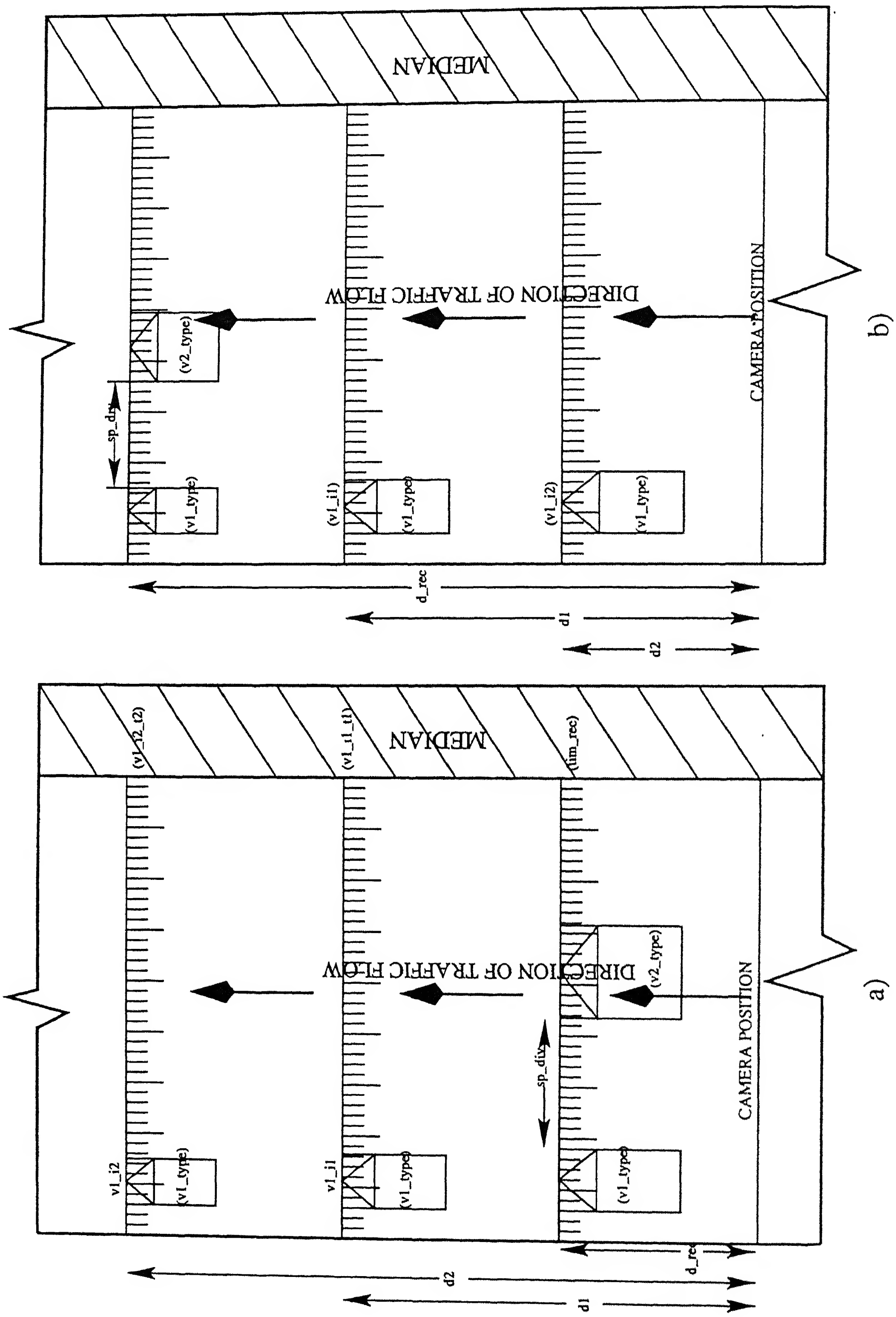


Figure 5.9: a) Positions of Vehicles for Lateral Space Computation by Method II ($d1 < d2, tim\_rec < v1\_i1\_t1$) b) Positions of Vehicles for Lateral Space Computation by Method II ($d1 \geq d2, tim\_rec \geq v1\_i1\_t1$)

5.5.5 Space Headway Study

Method I:- Space Headway Observations are at Fixed Locations

Let v_{fr} and v_{re} are the calculated speed of front and rear vehicles.
Spacing between two vehicles may be calculated as

$$\text{space} = (v_{re}\_t1 - v_{fr}\_t1) * v_{fr} - l_{fr}, \tag{5.11}$$

or

$$\text{space} = (v_{re}\_t2 - v_{fr}\_t2) * vfr - l_{fr}; \tag{5.12}$$

where space = spacing between front and rear vehicles
v_{re}_t1 = rear vehicle arrival time at first section
v_{re}_t2 = rear vehicle arrival time at second section
v_{fr}_t1 = front vehicle arrival time at first section
v_{fr}_t2 = front vehicle arrival time at second section
v_{fr} = velocity of front vehicle
l_{fr} = length of front vehicle

Method II:- Space Headway Observations are not at Fixed Locations

Let vf and vr ~~are~~ be the calculated speed of front and rear vehicles. a_tf and a_tr are the time of arrival of front and rear vehicle at any point whose coordinates are known.
Spacing between two vehicles can be calculated as

$$\text{space} = (a\_tr - a\_tf) * vf - l_{fr}; \tag{5.13}$$

5.5.6 Data for Calibration and Validation Study

Calibration and validation phase of the simulation model involves comparisons of the simulated and observed traffic flow characteristics. Observed data for traffic flow characteristics are extracted from the video data. This includes :

- At entry
  - Type of vehicle
  - Spot speed
  - Lateral position
  - Entry time
- At exit

- Type of vehicle
- Lateral position
- Exit time

Based on the observed data at entry and exit of the road section, the following measures are estimated:

- Journey speed distribution for all vehicle types.
- Time headway distribution at exit.
- Overtakings performed for different combination of vehicle groups.
- Traffic density of the road section.

First three measures are estimated for the selected period of study. Traffic density varies with time and is estimated at every 15 second interval. The statistics of these measures for the observed data are presented latter when validating the simulation model.

5.6 PARAMETER ESTIMATION

5.6.1 Time Headway Distributions

Time headway analysis is done for six data sets, each of one hour duration. Three sets of data are analysed for each direction of movement. The observed flow of each data set is presented in Table 5.6. It is observed that flow varies between 1700-2600 vph. The observed frequency distribution of time headways are given in Table 5.7 for two data sets, one for each direction. These observed time headway distributions are also shown in Figure 5.10 and Figure 5.11. It is observed that time headway distributions follow some form of exponential distribution. As the observed traffic volumes are very high and traffic consists of both constrained and free moving vehicles, it may be that headways consist of two separate distributions.

Schuhl (1955), Kell (1962), Greco et al. (1968), and Dawson (1968) suggested the use of composite headway distribution for motorised urban traffic. The composite headway distribution is represented as:

$$f(t) = (1 - \alpha)g(t) + \alpha h(t) \tag{5.14}$$

where f(t) = combined distribution
g(t) = headway distribution for free flowing vehicles
h(t) = headway distribution for constrained vehicles
α = proportion of constrained vehicles

Table 5.6: Observed Traffic Flow

S.NO.	Time of Data	Direction of Flow	Flow Rate (vph)
1	7-8 A.M.	Direction 1	1701
2	7-8 A.M.	Direction 2	2017
3	8-9 A.M.	Direction 1	2083
4	8-9 A.M.	Direction 2	1756
5	9-10 A.M.	Direction 1	2333
6	9-10 A.M.	Direction 2	2630

Direction 1: Barachaurah to Parade
Direction 2: Parade to Barachauraha

Table 5.7: Observed Time Headway Distributions

S.NO.	Time (sec.)	Frequency(h>t) Barachaurah-Parade (9.00 A.M.-10.00 A.M.)	Frequency(h>t) Parade-Barachaurah (8.00 A.M.-9.00 A.M.)
1	0.0	2333	1756
2	1.0	1253	1144
3	2.0	520	693
4	3.0	265	413
5	4.0	176	251
6	5.0	108	162
7	6.0	67	93
8	7.0	53	57
9	8.0	32	32
10	9.0	25	20
11	10.0	13	10
12	11.0	7	6
13	12.0	7	5
14	13.0	5	4
15	14.0	3	1
16	15.0	0	0

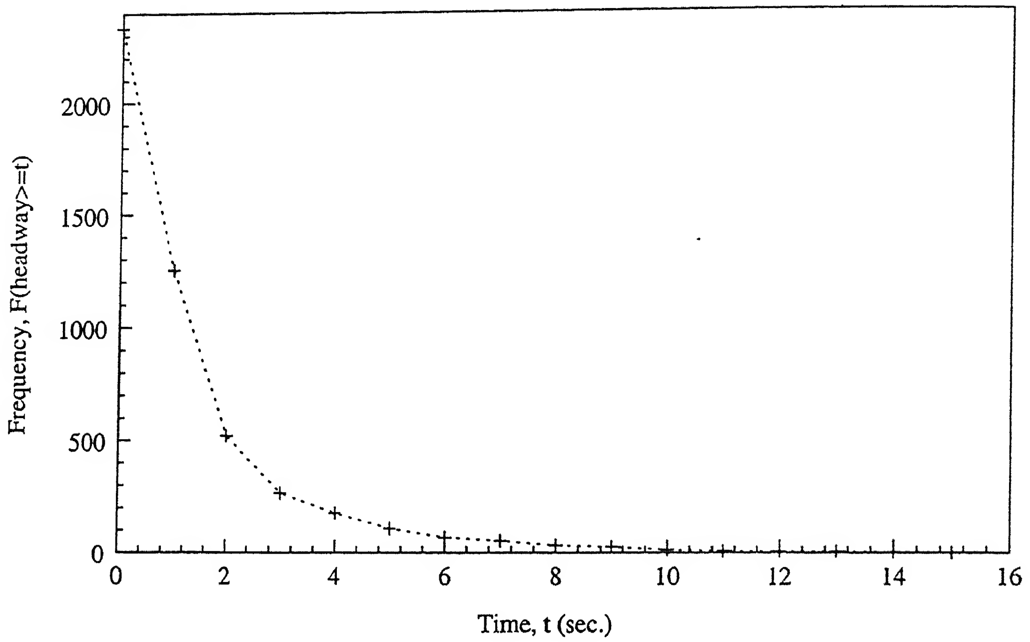


Figure 5.10: Observed Time Headway Distributions for Barachaurah-Parade (9.0-10.0 A.M.)

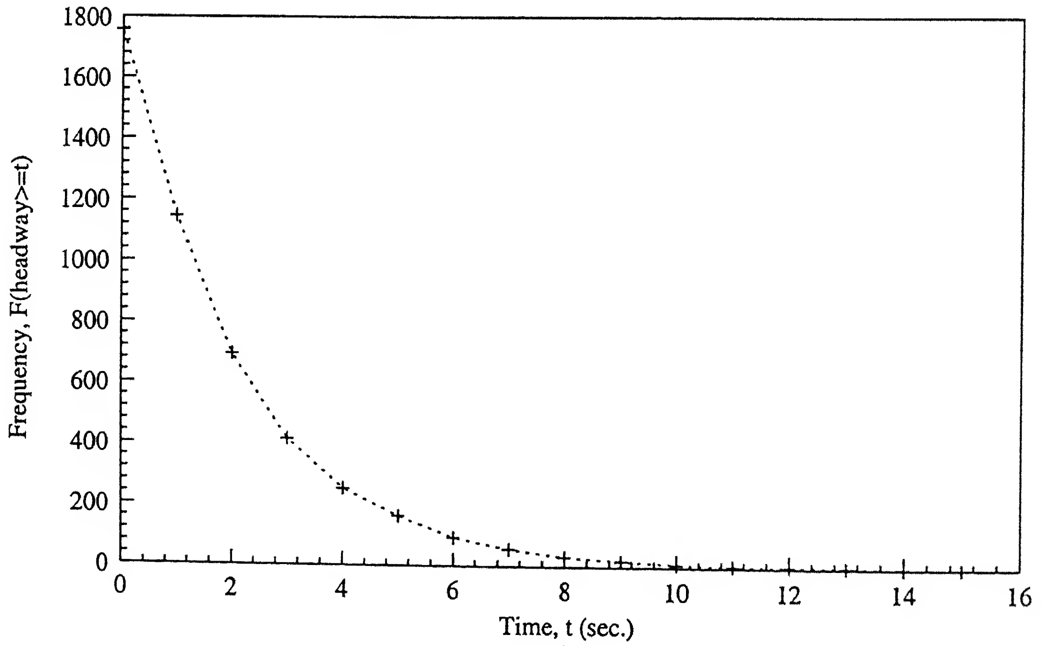


Figure 5.11: Observed Time Headway Distributions for Parade-Barachaurah, (8.0-9.0 A.M.)

For the observed time headways, the following three composite headway distributions have been considered for testing:

- Schuhl's composite headway distribution.
- Modified Schuhl's composite headway distribution in which time headways of motorised and non-motorised vehicles are segregated.
- Dawson's composite headway distribution.

Schuhl's Distribution

Schuhl suggested that headways consist of two subpopulations, one of free flowing vehicles and other of constrained vehicles. The proposed model is a composite of shifted and unshifted exponential distributions and is given by

$$p(h < t) = (1-\alpha)[1 - exp(\frac{-t}{T_1})] + \alpha[1 - exp(-\frac{t-\tau}{T_2-\tau})] \qquad for\ t \geq \tau \tag{5.15}$$

where $p(h < t)$	=	probability of headway less than t
h	=	time headway in seconds
α	=	fraction of total flow made up of constrained vehicles
T_1	=	average headway of free flowing vehicles in seconds
T_2	=	average headway of constrained vehicles in seconds
τ	=	shift of curve i.e. minimum headway for constrained vehicles in seconds

Schuhl's Distribution for segregated headways of motorised and non-motorised vehicles

In this distribution motorised and non-motorised vehicle headways have been separated. The segregation removes heterogeneity of vehicles in headway distributions. Also most of the motorised vehicles generally occupy the right side area of the road leaving the left side area to non-motorised vehicles. The proposed model is a composite of shifted and unshifted exponential distributions for motorised and non-motorised vehicles respectively and is given by

$$\begin{aligned} p(h < t) \quad = \quad & (\alpha_{un})[1 - exp(\frac{-t}{T_{n1}})] + \alpha_{cn}[1 - exp(-\frac{t-\tau_n}{T_{n2}-\tau_n}] \\ & +(\alpha_{um})[1 - exp(\frac{-t}{T_{m1}})] + \alpha_{cm}[1 - exp(-\frac{t-\tau_m}{T_{m2}-\tau_m})] \\ & for\ t \geq \tau_m, t \geq \tau_n \end{aligned} \tag{5.16}$$

where $p(h < t)$ = probability of headway less than t
α_{cn} = fraction of total flow made up of constrained NMV's
α_{cm} = fraction of total flow made up of constrained MV's
α_{un} = fraction of total flow made up of unconstrained NMV's
α_{um} = fraction of total flow made up of unconstrained MV's
T_{n1} = average headway of free flowing NMV's in seconds
T_{m1} = average headway of free flowing MV's in seconds
T_{n2} = average headway of constrained NMV's in seconds
T_{m2} = average headway of constrained MV's in seconds
τ_n = shift of curve (i.e. minimum headway) for constrained NMV's in seconds
τ_m = shift of curve (i.e. minimum headway) for constrained MV's in seconds
V = total number of vehicles arriving during time T

Dawson's Distribution

Dawson has combined the improved shape of the Erlang distribution and the feature of shifting the distribution to the right to account for the minimum headway. His version of model, known as Hyper-Erlang("hyperlang") distribution (Dawson and Chimini, 1968), may be expressed as

$$\begin{aligned} p(h \geq t) &= \alpha_1 e^{-\frac{t-\delta_1}{\gamma_1-\delta_1}} \\ &+\alpha_2 e^{-k\frac{t-\delta_2}{\gamma_2-\delta_2}} \sum_{x=0}^{k-1} k \frac{\frac{(t-\delta_2)^x}{(\gamma_2-\delta 2)}}{x!} \end{aligned} \tag{5.17}$$

where $p(h \geq t)$ = probability of headway greater than or equal to t
t = any time duration
δ_1 = the minimum "free" headway
γ_1 = the average "free" headway
δ_2 = the minimum headway in the constrained headway distribution
γ_2 = the average headway in the constrained distribution
k = an index that indicates the degree of non-randomness in the constrained headway distribution.

Here the value of k, a parameter that determines the shape of the distribution, may be estimated from the mean and variance of the observed data

$$k \approx \frac{T^2}{s^2} \tag{5.18}$$

where T = mean of the observed intervals
s^2 = variance of the observed intervals

In the Dawson's distribution value of k is rounded off to the nearest integer.

Analysis and Interpretation of Results

The parameters for the above three mentioned headway distributions are estimated for each of the six data sets. The parameters are estimated based on every alternate observed headway. The other alternate observed headways are used for comparison of observed and fitted headways. The estimated values of the parameters are presented in Table 5.8 and Table 5.9.

Table 5.8: Estimated Parameters of Schuhl's Distribution for Time Headway

Data Set	Direction of Flow	α	T_1 sec.	T_2 sec.	τ sec.
1	Direction 1	0.82	2.26	1.46	0.00
2	Direction 1	0.68	2.02	1.11	0.00
3	Direction 1	0.38	2.22	1.11	0.00
4	Direction 2	0.74	1.96	1.29	0.00
5	Direction 2	0.70	2.22	1.58	0.00
6	Direction 2	0.40	1.74	1.12	0.00

Direction 1: Barachaurah to Parade
Direction 2: Parade to Barachauraha

Table 5.9: Estimated Parameters of Modified Schuhl's Distribution for Time Headway

Data Set	Direction of Flow	α_{cn}	α_{cm}	α_{un}	α_{cn}	T_{n1} sec.	T_{m1} sec.	T_{n2} sec.	T_{m2} sec.	τ_n sec.	τ_m sec.
1	Direction 1	0.07	0.11	0.55	0.27	2.21	2.35	1.52	1.42	0.0	0.0
2	Direction 1	0.17	0.16	0.49	0.19	1.88	2.41	0.97	1.26	0.0	0.0
3	Direction 1	0.39	0.22	0.26	0.12	1.99	2.68	0.96	1.99	0.0	0.0
4	Direction 2	0.09	0.17	0.50	0.24	1.77	2.36	1.26	1.30	0.0	0.0
5	Direction 2	0.11	0.19	0.43	0.27	2.02	2.52	1.68	1.52	0.0	0.0
6	Direction 2	0.27	0.33	0.27	0.13	1.62	1.99	0.98	1.22	0.0	0.0

Direction 1: Barachaurah to Parade
Direction 2: Parade to Barachauraha

Theoretical frequencies of arrival gaps, as obtained for different fitted distributions, are computed and compared with the observed frequencies. Goodness of Fit is tested by K-S test. Value of the K-S test statistic for 0.05 and 0.01 level of significance can be calculated

by $\frac{1.36}{\sqrt{n}}$ and $\frac{1.63}{\sqrt{n}}$; where n is a sample size for $n \geq 35$. In the present analysis as the sample size is much more than 35, the above mentioned K-S statistics relationships are adopted. Results of the K-S test are presented in Table 5.10 both for Schuhl's and Modified-Schuhl's distributions.

Table 5.10: Summary of the Results of Time-Headway Analysis with K-S Test

S.No.	Time	Flow Rate (vph)	Direction of Flow	Observed		Theoretical	
				Schuhl K-S Value	Mod. Schuhl K-S Value	0.05 Level K-S Value	0.01 Level K-S Value
1	7-8 A.M.	1701	Direction 1	0.015	0.016	0.047	0.056
2	7-8 A.M.	2017	Direction 2	0.038	0.043	0.043	0.051
3	8-9 A.M.	2083	Direction 1	0.033	0.033	0.042	0.051
4	8-9 A.M.	1756	Direction 2	0.040	0.043	0.046	0.055
5	9-10 A.M.	2333	Direction 1	0.045	0.043	0.040	0.048
6	9-10 A.M.	2630	Direction 2	0.052	0.054	0.038	0.045

Direction 1: Barachaurah to Parade
Direction 2: Parade to Barachauraha

For Modified-Schuhl's distribution, in which time headways of motorised and non-motorised vehicles are segregated, comparison indicates that the observed K-S value is less than the critical K-S value in most of the cases both for 0.05 and 0.01 level of significance. Same is the case for Schuhl's distribution. However, for high flow rates, observed K-S values are slightly higher than theoretical value in some cases, both for Schuhl's and Modified-Schuhl's distributions.

Comparison of observed and fitted Schuhl's distributions are shown in Figures 5.12 to 5.13. Comparison between observed and fitted Modified-Schuhl's distributions are shown in Figures 5.14 to 5.15. Analysis indicates that both Schuhl's and Modified Schuhl's distributions can be used to describe the time headway distributions for urban heterogeneous traffic. The Modified-Schuhl's distribution, as formulated in this analysis, is more appropriate as motorised vehicles and non-motorised vehicles are segregated. The only limitation of this distribution is that more number of parameters are to be estimated.

Dawson's distribution is also tested for all the six hour data sets. It is estimated that the value of k parameter is 1. k is an index that indicates the degree of non-randomness in the constrained headway distribution and thus determines the shape of the distribution. With

the value of $k = 1$, Dawson's distribution tends to Schuhl's distribution (Equation 5.17). Therefore, no further testing of Dawson's distribution is attempted.

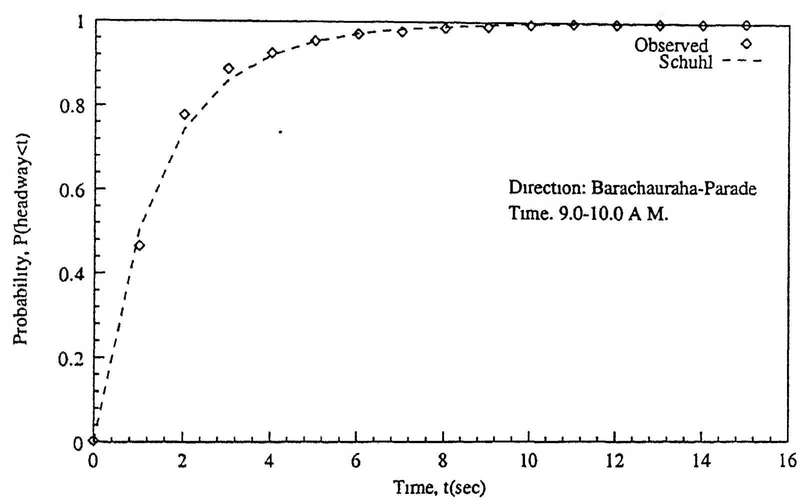


Figure 5.12: Observed and Fitted Time Headway Distributions (Schuhl's Composite Headway Distribution)

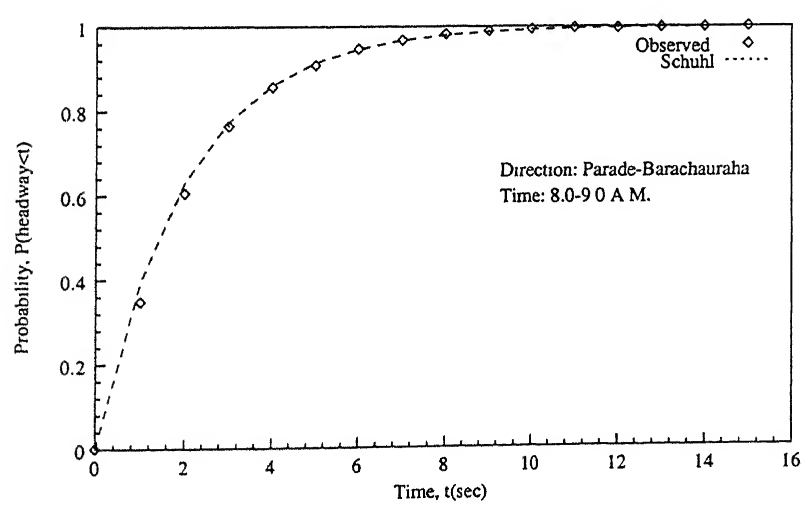


Figure 5.13: Observed and Fitted Time Headway Distributions (Schuhl's Composite Headway Distribution)

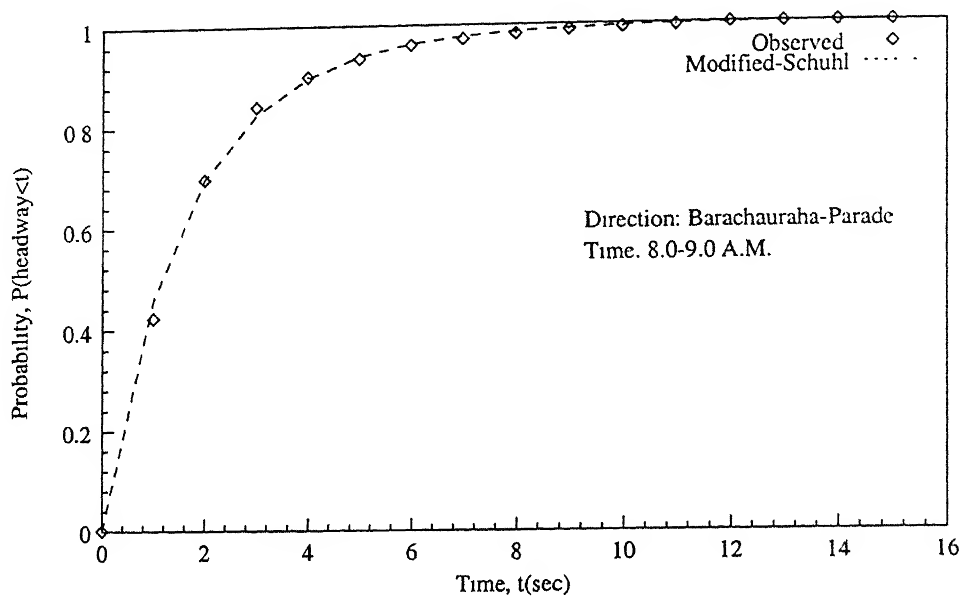


Figure 5.14: Observed and Fitted Time Headway Distributions (Modified-Schuhl's Composite Headway Distribution)

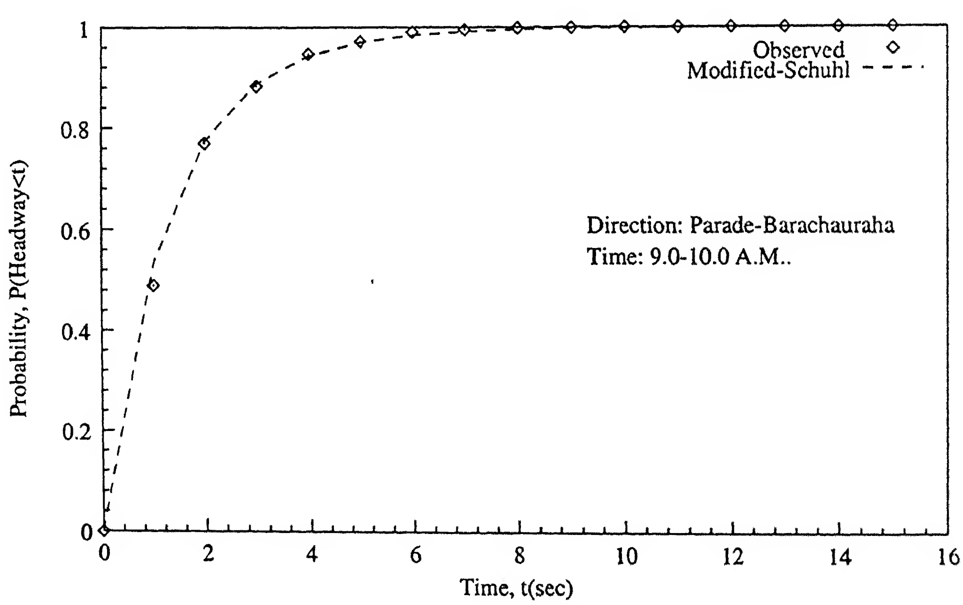


Figure 5.15: Observed and Fitted Time Headway Distributions (Modified-Schuhl's Composite Headway Distribution)

5.6.2 Free Speed Distributions

Free speed observations are made with radar speedometers and also extracted from the video images for different types of vehicles. The observed frequency distributions of the free speeds are given in Table 5.11 and Table 5.12 for some types of non-motorised and motorised vehicles. The observed frequency distribution is also shown in Figure 5.16 for bicycle. Cumulative frequency distribution is also shown in Figure 5.17 for scooter and tempo. Observations show that the free speeds tend to follow a normal type of distribution. For some vehicle type like Maruti Van distributions are slightly skewed. In a related study (CRRI, 1991) of Traffic simulation modelling on Indian Highways, where large scale free speed observations were made, it is concluded that free speeds (basic desired speeds) are normally distributed.

Table 5.11: Observed Free Speed Distributions for Non-Motorised Vehicles

Free Speed	Frequency	
Interval (m/sec)	Bicycle	Cycle Rickshaw
2.00-2.50	0	0
2.50-3.00	3	0
3.00-3.50	11	5
3.50-4.00	29	12
4.00-4.50	44	13
4.50-5.00	41	10
5.00-5.50	28	2
5.50-6.00	14	0
6.00-6.50	4	1
Total	174	43

Normal distribution was fitted for all the vehicles types and the parameters of the distribution (mean, standard deviation) are presented in Table 5.13. Chi-Square test is used to determine the goodness of fit. Table 5.13 indicates the observed Chi-Square values against the critical Chi-Square value for 0.05 and 0.01 level of significance. The observed Chi-Square value is less than critical value for all the cases at 0.01 level of significance. At 0.05 level of significance, the observed statistics are marginally higher than the theoretical value for two cases (Scooter and Tempo).

At 0.01 level of significance, observed Chi-Square are less than critical Chi-Square values for all the cases. Observed and calculated cumulative free speed frequency distributions are

Table 5.12: Observed Free Speed Distributions for Motorised Vehicles

Free Speed Interval (m/sec)	Frequency			
	LCV	Maruti Car	Scooter	Tempo
6.0-7.0	0	0	0	6
7.0-8.0	0	0	0	49
8.0-9.0	0	0	0	86
9.0-10.0	4	0	9	64
10.0-11.0	28	0	73	45
11.0-12.0	32	10	74	6
12.0-13.0	11	16	43	0
13.0-14.0	2	15	12	1
14.0-15.0	0	7	0	0
15.0-16.0	0	3	0	0
16.0-17.0	0	0	1	0
Total	77	51	212	257

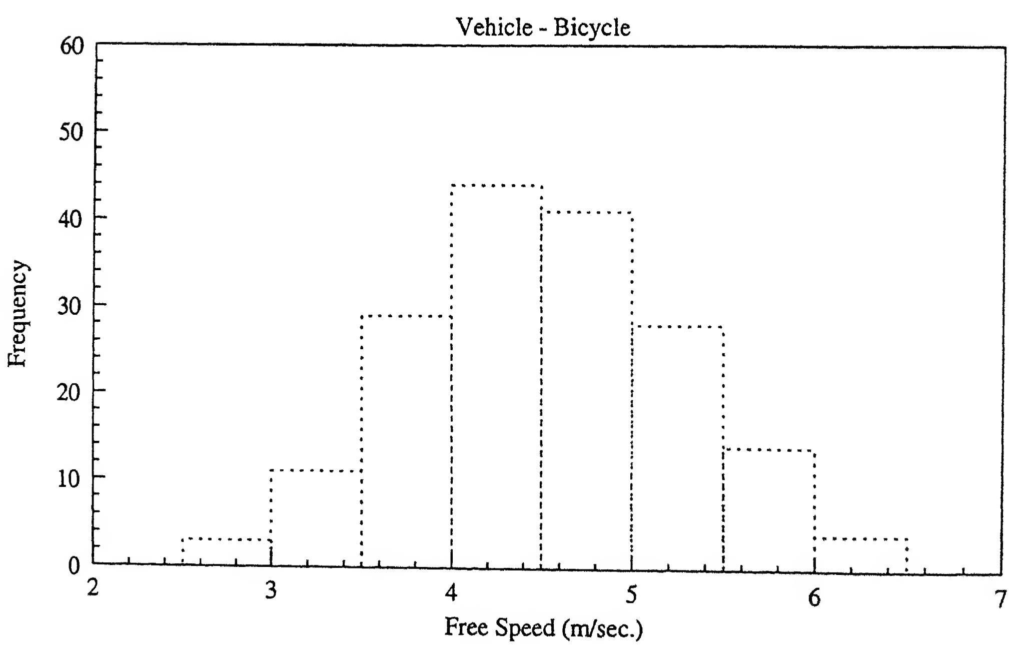


Figure 5.16: Observed Free Speed Frequency Distribution of Bicycle

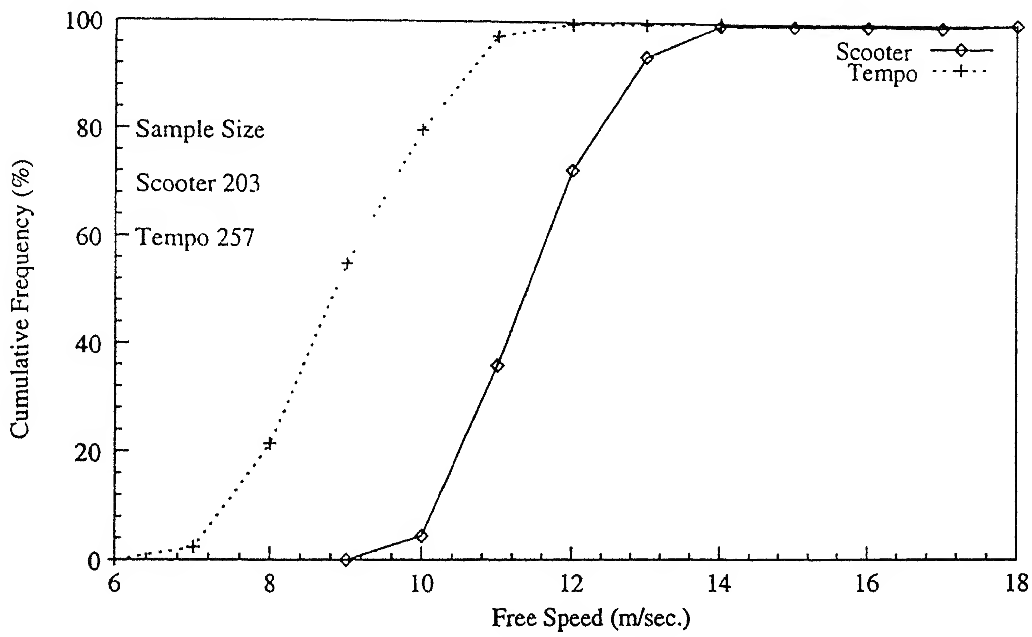


Figure 5.17: Cumulative Frequency Distribution of Observed Free Speeds for Scooter and Tempo

shown in Figures 5.18 to 5.20 for some types of vehicles. The shape of the observed and theoretical frequencies are identical with variations only at low speed values. Based on this analysis, it is concluded that free speed distributions follow normal distribution.

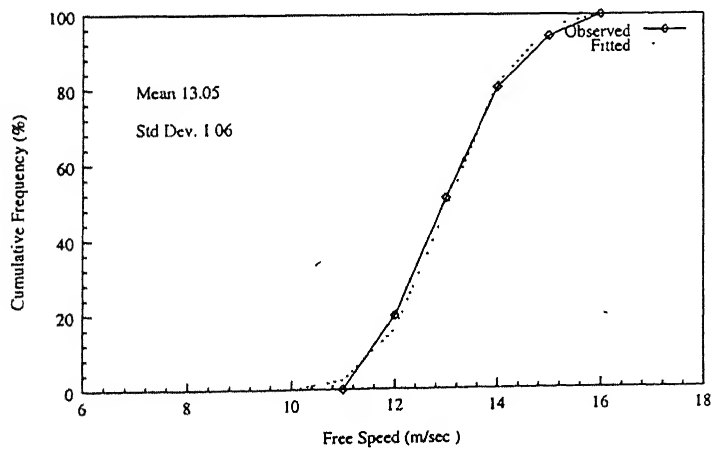


Figure 5.18: Observed and Fitted Free Speed Distributions of Maruti Car

Table 5.13: Summary of the Results of Free Speed Analysis

S.No	Vehicle Type	Sample Size	Free Speed		Observed	Theoretical	
			Mean (m/sec.)	Std.Dev. (m/sec.)	Chi-Square Value	Chi-Square at 0.05 Level	Chi-Square at 0.01 Level
1	Moped	52	10.23	1.03	2.25	7.81	11.30
2	Bus	41	11.75	1.27	2.91	9.49	13.30
3	Auto Rick	51	9.05	0.39	0.34	3.84	6.63
4	Fiat	63	12.90	1.07	4.98	7.81	11.30
5	Ambassador	68	13.28	1.16	4.61	7.81	11.30
6	Maruti Car	51	13.05	1.06	3.87	7.81	11.30
7	Maruti Van	61	12.57	0.84	4.93	5.99	9.21
8	Jeep Mahin.	63	12.57	0.88	4.85	5.99	9.21
9	Scooter	212	11.39	1.09	9.62	*9.49	13.30
10	Motor Cycle	63	13.44	1.19	2.90	9.49	13.30
11	L.C.V.	77	11.20	0.81	0.74	5.99	9.21
12	Tempo	257	8.91	1.08	9.90	*9.49	13.30
13	Bicycle	174	4.51	0.75	0.65	11.10	15.10
14	Cycle-Rick	43	4.14	0.61	2.50	7.81	11.30
15	Push Cart	10	1.58	0.43	0.32	3.84	6.63
16	Horse Cart	9	2.64	0.09	0.48	3.84	6.63

Std.Dev.: Standard Deviation
Note: * denotes Chi-Square test failed for 0.05 level of significance.

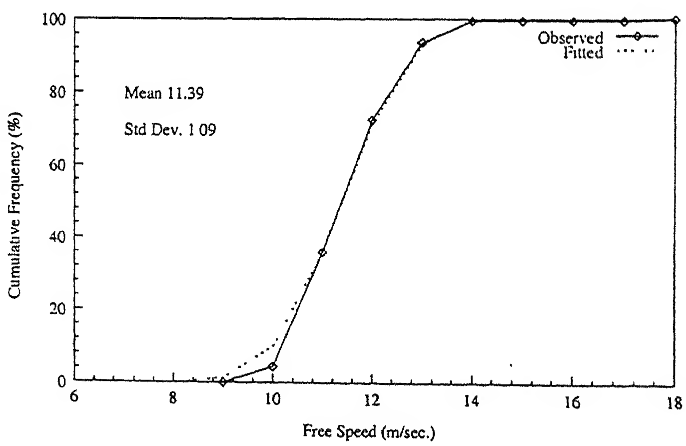


Figure 5.19: Observed and Fitted Free Speed Distributions of Scooter

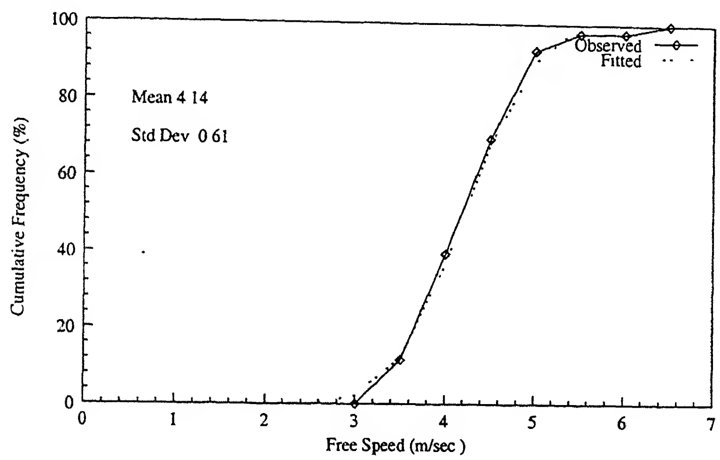


Figure 5.20: Observed and Fitted Free Speed Distributions of Cycle Rickshaw

5.6.3 Lateral Space Distributions And Their Parameters

Lateral Clearances

Vehicles moving in traffic stream maintain certain lateral clearances from other vehicles and also with respect to fixed road side objects such as median, kerb, etc. Detailed study of lateral space is of prime importance in processing the flow behaviour of vehicles in traffic simulation modelling.

Some studies have reported their inferences on space headway and lateral clearances of vehicles. Tuladhar (1987) studied the longitudinal and lateral clearances for determination of influence areas of vehicles, based on a concept called space coefficients of vehicles. Nagraj et al.(1990) also studied the longitudinal and lateral placement of vehicles in mixed traffic conditions through video recording. In their study they have adopted probabilistic approach to evaluate space coefficients. Doughery et al. (1993) used neural network to predict and classify traffic congestion. Hsiao et al. (1994) applied fuzzy logic and neural networks to predict the traffic congestion due to roadway incidents. Anjaneyulu et al. (1997) used neural networks to model linear and lateral spacing of vehicles in mixed traffic. Different longitudinal and lateral spacing polynomials, which are functions of flow, have been derived from the neural network models.

None of the above studies considered the speed of interacting vehicles in determining longitudinal and lateral clearances. In this study an attempt has been made to develop relations between lateral space and speed of interacting vehicles. Relations have also been

developed for vehicle interactions with physical barriers like median and kerb etc.

Recorded video data was analysed to extract the following information with respect to interacting vehicles.

- Lateral spacing between the overtaking and overtaken vehicles when both are parallel.
- Speed of overtaking vehicle when parallel to overtaken vehicle.
- Speed of the overtaken vehicle

Information from video recording was available for about 2000 vehicles and it was aggregated into different groups of overtaking and overtaken vehicles. As the traffic has been categorised into eight groups, there are 64 combinations of overtaking and overtaken vehicle groups. Sample size of the extracted information was sufficient for those cases where overtakings generally occur. But in certain cases, where slow moving vehicles like push carts are involved, the sample size was quite small.

The relationship between the observed lateral spacing and the vehicle speed are shown in Figures 5.21 to 5.23 for some vehicles. Each vehicle maintains a certain minimum clearance to avoid lateral collision. However, as the speed of the vehicle increases, it has a tendency to maintain higher lateral spacing. Data in Figures 5.21 to 5.23 show that lateral spacing varies with speed upto a certain level beyond which speed does not affect lateral clearance. This indicates lateral space has two threshold values of minimum and maximum lateral clearance.

The recorded data set is used to estimate the following:

- Minimum lateral clearance
- Maximum lateral clearance
- Mean and standard deviation of observed lateral clearances

Results indicate that there is wide dispersion between the observed minimum and maximum lateral spacings. For the Car group, the minimum lateral clearance with respect to other motorised vehicles is about 0.17-0.18 metre, whereas the maximum lateral clearance lies with in the range of 1.30-1.40 metre. The mean observed lateral spacing is 0.54 metre with standard deviation of 0.23 metre. The lateral space values for Car group with respect to bicycles are on the lower side varying between 0.20-0.97 metre. Estimated values for different combinations are presented in Table 5.14.

Observed lateral space study data is utilised in the simulation model for the following processes:

- Decision making process for overtaking and yielding.

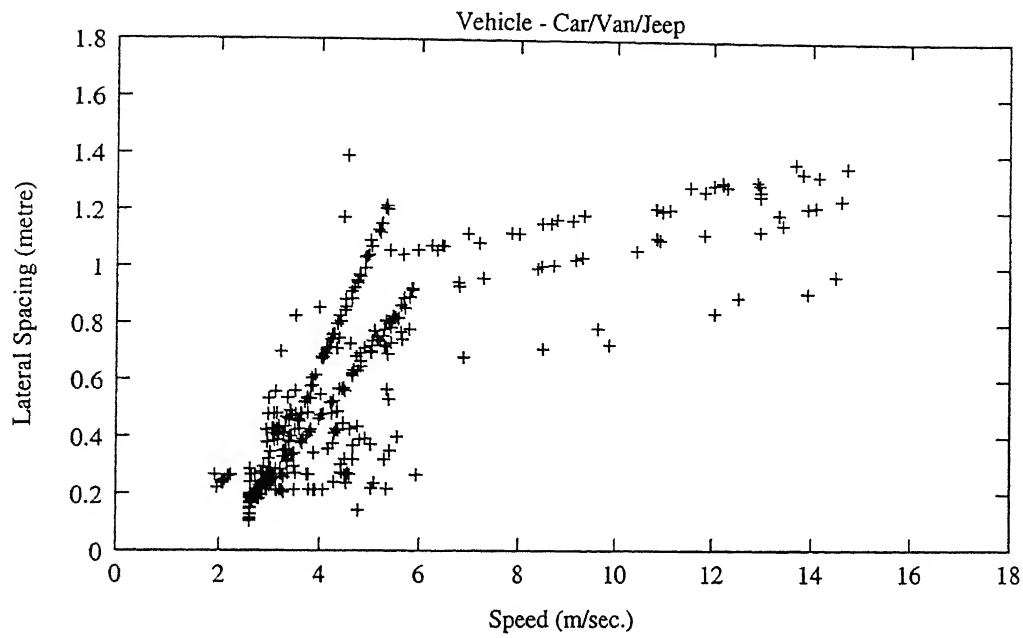


Figure 5.21: Observed Lateral Spacings for Car/Van/Jeep

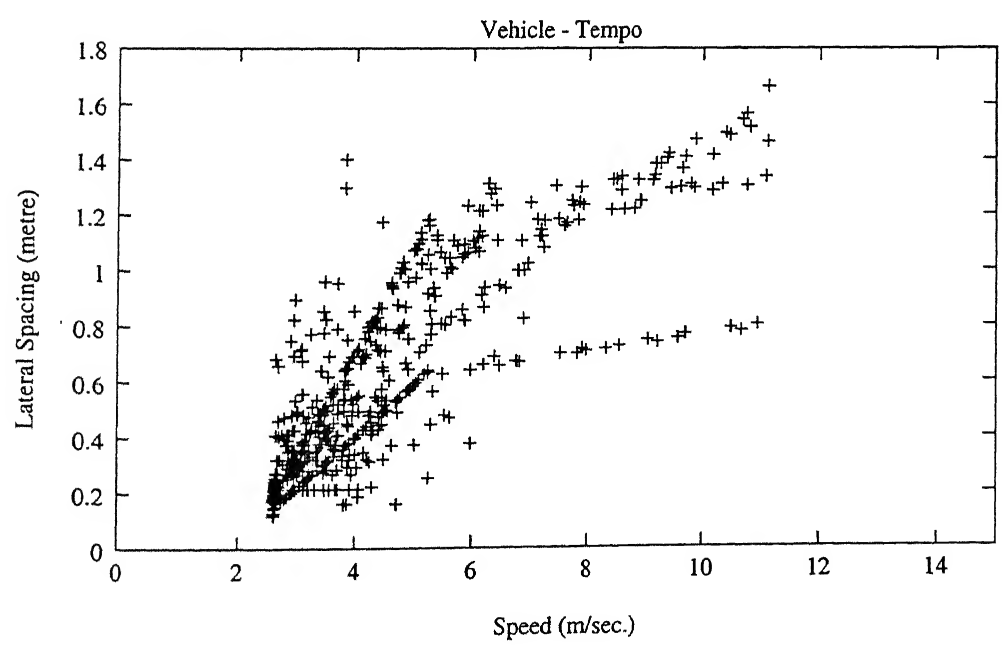


Figure 5.22: Observed Lateral Spacings for Tempo

Table 5.14: Distribution of Lateral Spacings for Different Combinations of Vehicle Group Interactions

Overtaking Group		Overtaken Vehicle Group							
		1	2	3	4	5	6	7	8
1 (Car/Van/Jeep)	Mean .	0.53	0.55	0.55	0.55	0.34	0.40	0.41	0.40
	St. Dev.	0.23	0.25	0.24	0.24	0.19	0.15	0.15	0.15
	Minimum	0.17	0.17	0.17	0.17	0.18	0.18	0.20	0.18
	Maximum	1.36	1.37	1.31	1.31	1.39	0.92	0.97	0.92
2 (Tempo)	Mean	0.54	0.31	0.54	0.54	0.30	0.40	0.46	0.40
	St. Dev.	0.23	0.15	0.23	0.23	0.11	0.17	0.22	0.17
	Minimum	0.17	0.10	0.18	0.18	0.12	0.10	0.13	0.03
	Maximum	1.31	1.01	1.33	1.33	0.80	1.30	1.52	1.30
3 (LCV)	Mean	0.53	0.51	0.53	0.53	0.35	0.48	0.47	0.48
	St. Dev.	0.23	0.24	0.23	0.23	0.14	0.19	0.22	0.19
	Minimum	0.17	0.16	0.17	0.17	0.11	0.18	0.21	0.18
	Maximum	1.37	1.59	1.32	1.32	0.97	1.09	1.48	1.09
4 (Bus)	Mean	0.53	0.51	0.53	0.53	0.35	0.48	0.47	0.48
	St. Dev.	0.23	0.24	0.23	0.23	0.14	0.19	0.22	0.19
	Minimum	0.17	0.16	0.17	0.17	0.11	0.18	0.21	0.18
	Maximum	1.37	1.59	1.32	1.32	0.97	1.09	1.48	1.09
5 (Motorised Two Wheelers)	Mean	0.34	0.36	0.34	0.34	0.30	0.36	0.34	0.36
	St. Dev.	0.18	0.17	0.18	0.18	0.18	0.18	0.14	0.18
	Minimum	0.10	0.10	0.12	0.12	0.10	0.11	0.12	0.11
	Maximum	1.39	1.40	1.39	1.39	1.40	1.40	1.11	1.40
6 (Push Cart/ADV)	Mean						0.31		
	St. Dev.	—	—	—	—	—	0.15	—	—
	Minimum	—	—	—	—	—	0.10	—	—
	Maximum						1.01		
7 (Bicycle)	Mean						0.28	0.25	0.28
	St. Dev.	—	—	—	—	- -	0.10	0.10	0.10
	Minimum	—	—	—	—	—	0.10	0.12	0.11
	Maximum						0.79	0.71	0.79
8 (Cycle Rickshaw)	Mean						0.31	0.28	0.31
	St. Dev.	—	—	—	—	—	0.15	0.10	0.15
	Minimum	—	—	—	—	—	0.10	0.09	0.11
	Maximum						1.01	0.78	1.01

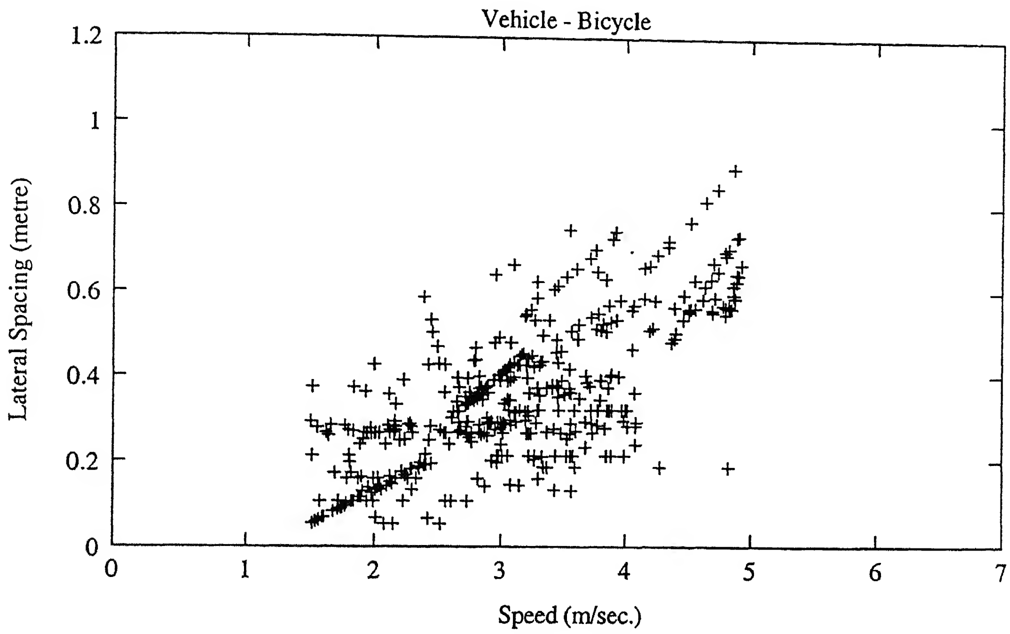


Figure 5.23: Observed Lateral Spacings for Bicycle

- Performance process to estimate the speed of the overtaking vehicle when passing by the side of overtaken vehicle.

Overtaking/Yielding Decision Process

The probability of overtaking and yielding in a situation depends upon the available lateral space. Based on the results, the probability of overtaking varies linearly with the available lateral space subject to constraint of minimum and maximum lateral space of the relevant group. If the IVLS is less then minimum inter-vehicular lateral spacing ($IVLS_{MIN_{OV}}$), the probability for overtaking is zero and for IVLS more then maximum inter-vehicular lateral spacing ($IVLS_{MAX_{OV}}$), the probability is one. For in between values, probability varies linearly and is expressed as:

$$prob_{ov} = \begin{cases} 0 & x < IVLS_{MIN_{OV}} \\ \frac{x - IVLS_{MIN_{OV}}}{IVLS_{MAX_{OV}} - IVLS_{MIN_{OV}}} & IVLS_{MIN_{OV}} \leq x \leq IVLS_{MAX_{OV}} \\ 1 & x > IVLS_{MAX_{OV}} \end{cases} \tag{5.19}$$

The yielding behaviour of front vehicle is also stochastic in nature and is dependent on inter-

vehicular lateral spacing between the two vehicles. If the inter-vehicular lateral spacing is less than $IVLS_{MIN_Y}$ then the front vehicle will definitely yield and if the inter-vehicular lateral spacing is greater then $IVLS_{MAX_Y}$ then vehicle will not yield. Probability function is represented as

$$prob_{yd} = \begin{cases} 1 & x < IVLS_{MIN_Y} \\ \frac{IVLS_{MAX_Y} - x}{IVLS_{MAX_Y} - IVLS_{MIN_Y}} & IVLS_{MIN_Y} \leq x \leq IVLS_{MAX_Y} \\ 0 & x > IVLS_{MAX_Y} \end{cases} \tag{5.20}$$

Estimation of Overtaking Speed

Lateral space study data for different combinations is analysed to estimate the speed of overtaking vehicles when passing by the side of vehicle being overtaken. The relationship between the lateral spacing and the overtaking speed for the observed data points is shown in Figure 5.24. It is observed that the overtaking vehicle speed increases with lateral spacing, which is quite logical.

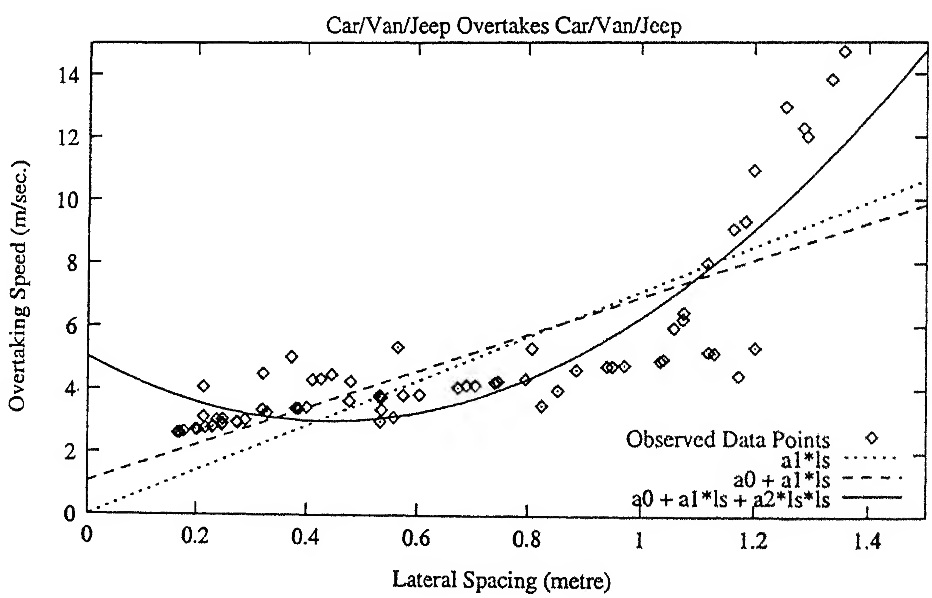


Figure 5.24: Overtaking Speed - Lateral Space Relationship for Car/Van/Jeep Overtakes Car/Van/Jeep

The relationship between the overtaking vehicle speed, overtaken vehicle speed and lateral spacing are shown in the Figures 5.25-5.27 for observed data points. It is seen from

these figures that overtaking vehicle speed also depends upon the overtaken vehicle speed, though its effect is not as significant as in case of lateral spacing.

To estimate the overtaking vehicle speed, the following three relationships are adopted and their parameters are estimated.

$$\textbf{pol1}: ovt_{vel} = a_1 l_s, \tag{5.21}$$

$$\textbf{pol2}: ovt_{vel} = a_2 l_s + a_3 ovn_{vel}, \tag{5.22}$$

$$\textbf{pol3}: ovt_{vel} = a_4 l_s + a_5 ovn_{vel} + a_6 l_s^2 + a_7 ovn_{vel}^2 + a_8 l_s ovn_{vel}; \tag{5.23}$$

where ovt_{vel} = speed of overtaking vehicle
ovn_{vel} = speed of overtaken vehicle
l_s = Lateral space available on the side of vehicle during overtaking operation
$a_1, a_2, \ldots\ldots a_8$ = coefficients

In the first relationship (pol1), the overtaking speed is considered to vary linearly with lateral spacing. Higher order polynomials are also tried for this relationship, but there is no significant improvement in the statistics.

For the second and third relationships, the overtaking vehicle speed is considered to vary both with lateral spacing and overtaken speed. For the second relationship (pol2), variation is linear, whereas for the third relationship (pol3), variation is of quadratic nature.

The estimated coefficients for the three relationships are presented in Table 5.15 for different feasible combinations of vehicle group interactions. The fitted linear and quadratic surfaces (pol2 and pol3) are shown in Figures 5.28 to 5.31 along with the data points. It is observed that both the surfaces fit well for the range of observed data. However, the quadratic fit shows abrupt change outside the fitted range in some cases. For the simulation model, the linear relationship (pol2) equation 6.14 is adopted for estimating the speed of overtaking vehicles.

Estimation of Lateral Space from Physical Barriers

Vehicles moving in a traffic stream maintain certain clearance from road side object such as median, kerb, etc. The estimation of this lateral clearance is necessary to process the flow of vehicles in the simulation model. Information of lateral spacing from the road side objects was extracted from video data for different types of vehicles. In all about 400 observations of this lateral spacing are analysed. Extracted data includes:

- Vehicle Type
- Speed of the vehicle

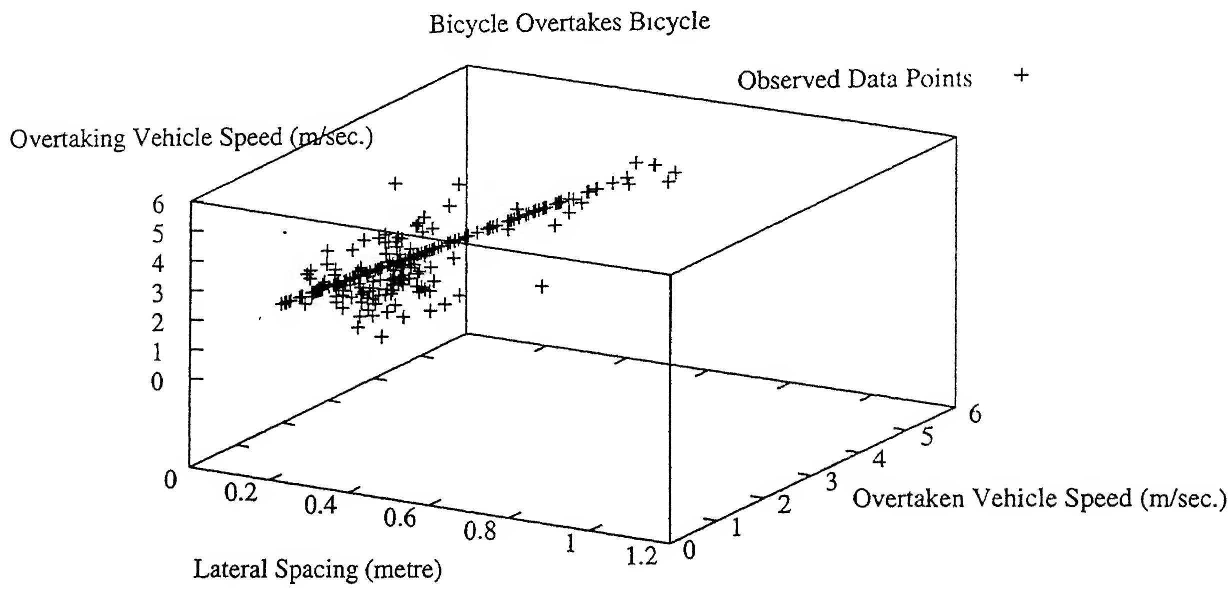


Figure 5.25: Observed Lateral Spacings for Bicycle overtakes Bicycle

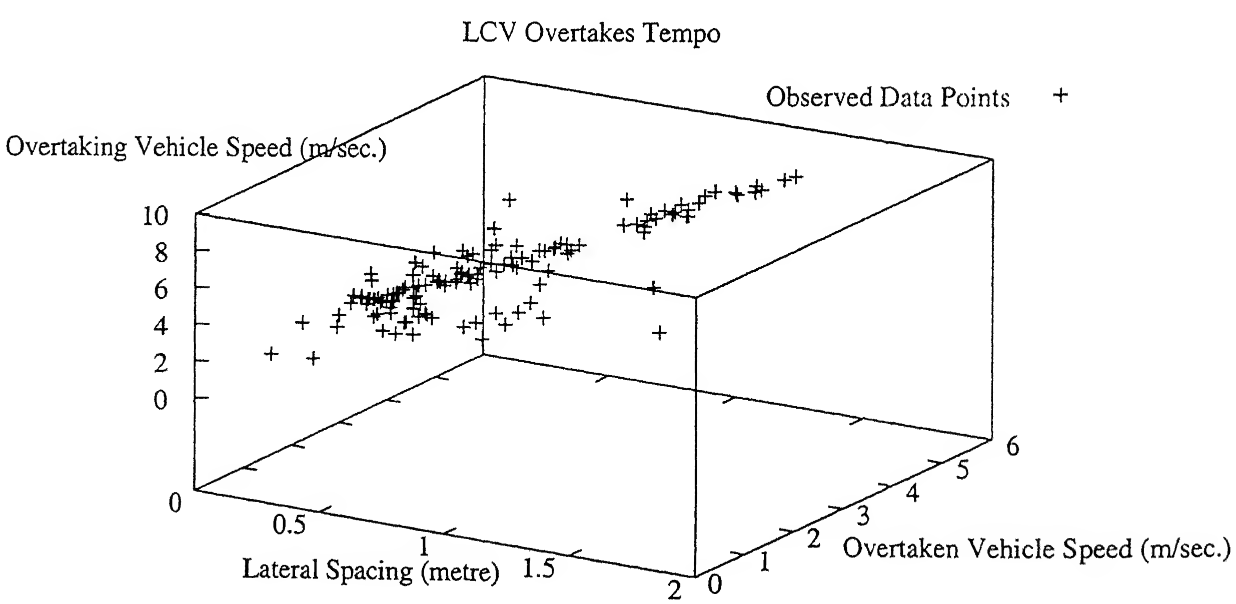


Figure 5.26: Observed Lateral Spacings for LCV overtakes Tempo

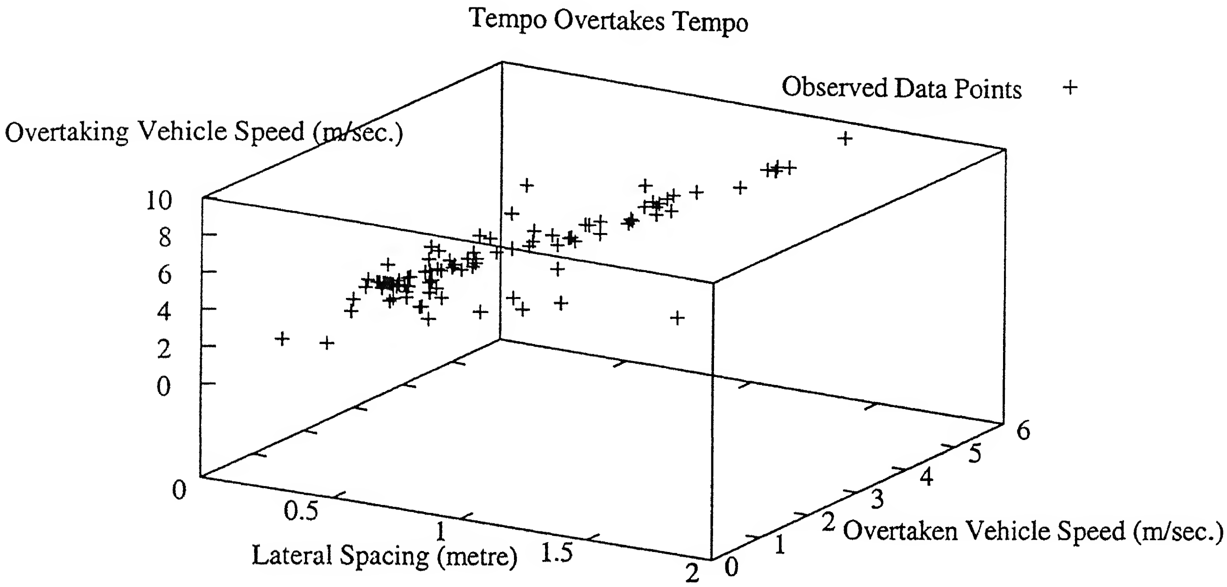


Figure 5.27: Observed Lateral Spacings for Tempo overtakes Tempo

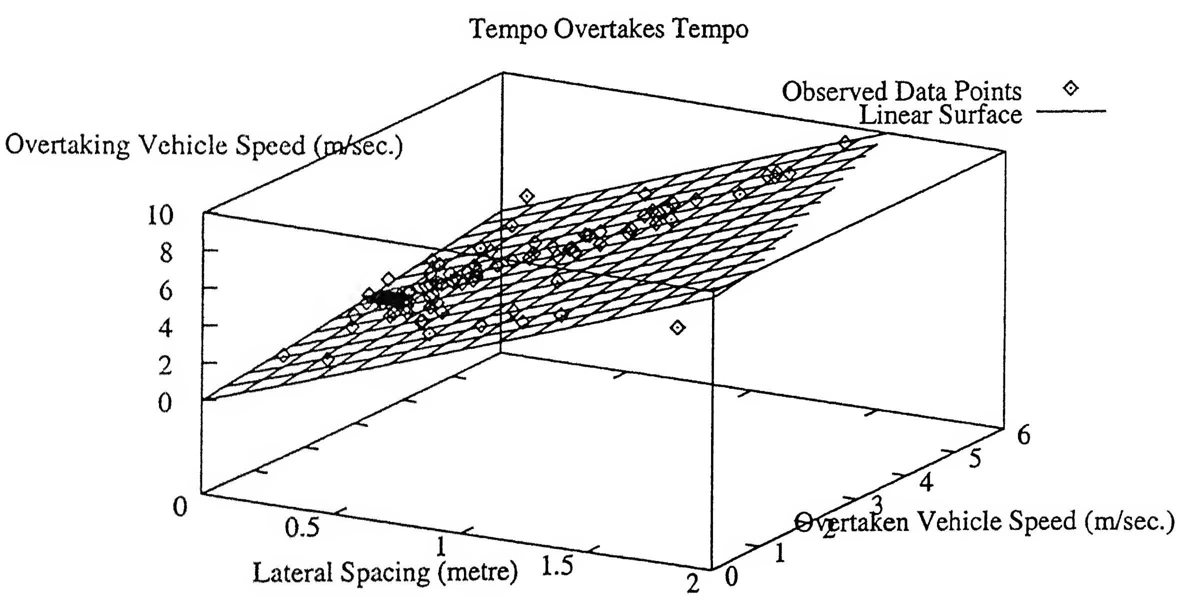


Figure 5.28: Overtaking Speed Polynomials for Tempo Overtakes Tempo (Linear Surface)

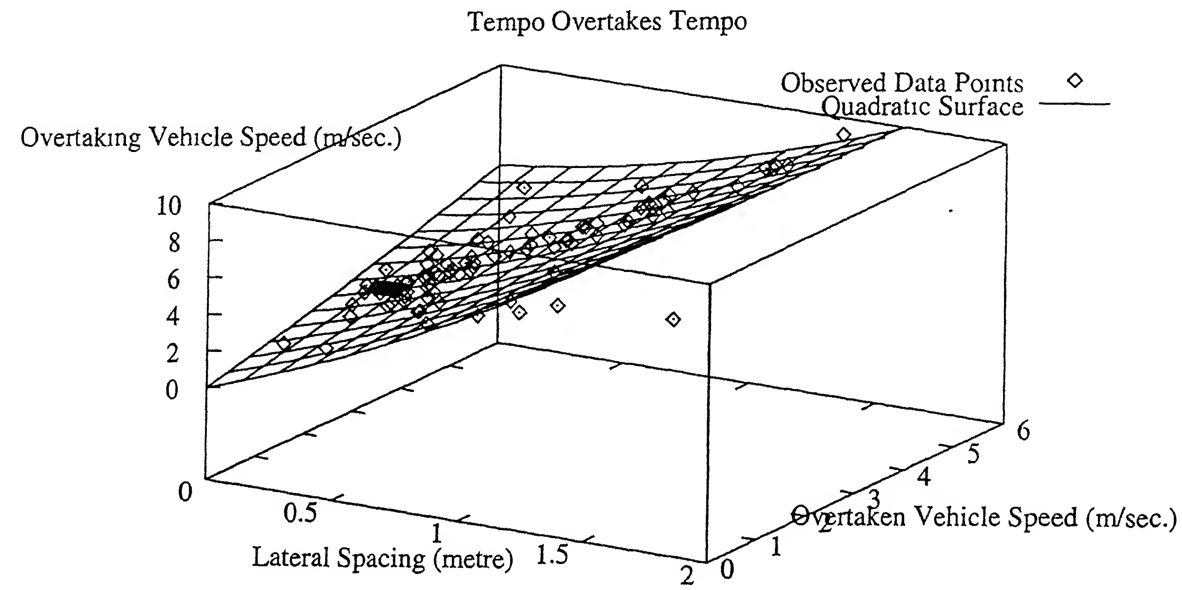


Figure 5.29: Overtaking Speed Polynomials for Tempo Overtakes Tempo (Quadratic Surface)

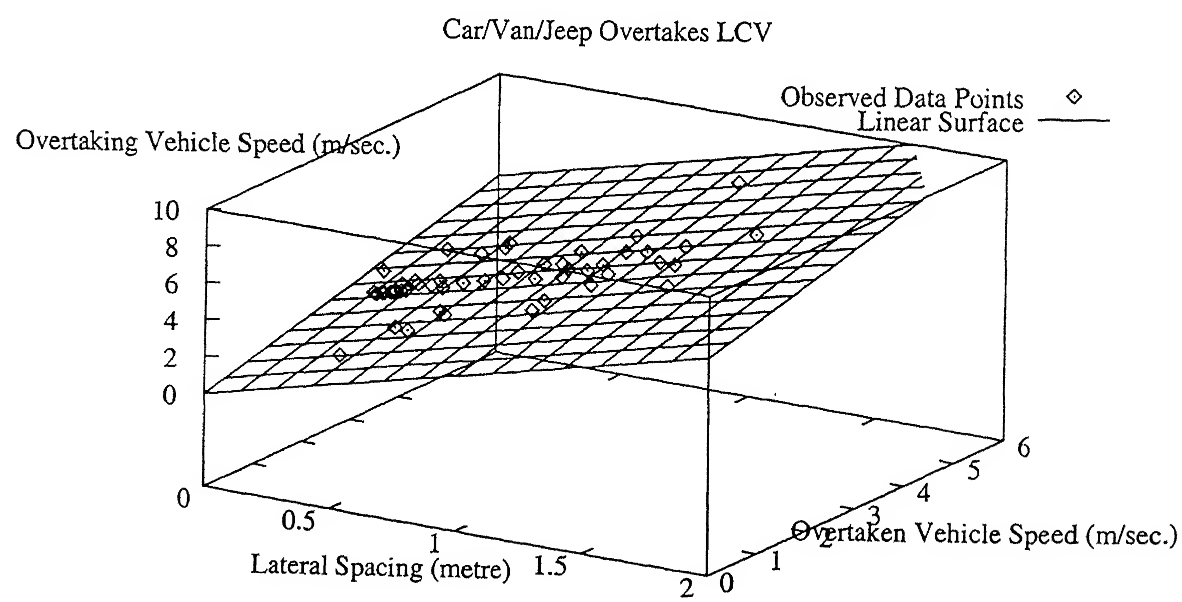


Figure 5.30: Overtaking Speed Polynomials for Car/Van/Jeep Overtakes LCV (Linear Surface))

Table 5.15: Coefficients of Overtaking Speed Polynomials

Overtaking Vehicle Group	Overtaken Vehicle Group	Polynomial Coefficients							
		a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
1	1	7.097	3.787	0.685	2.831	0.629	5.885	0.209	2.134
1	2	6.923	2.861	0.853	0.289	1.046	5.327	0.090	1.136
1	3	7.002	3.336	0.757	0.865	1.018	2.171	0.016	0.115
1	5	8.924	3.807	0.782	1.366	1.028	1.170	0.039	0.252
1	7	8.476	6.668	0.393	15.502	4.395	22.339	0.821	0.255
1	8	9.109	10.439	0.293	17.822	5.125	32.436	0.799	2.492
2	1	6.149	3.381	0.631	3.629	0.676	2.086	0.093	1.044
2	2	5.410	2.115	0.829	2.342	1.060	1.684	0.023	0.854
2	3	6.176	3.994	0.515	2.716	0.702	5.558	0.203	2.178
2	5	10.542	4.933	0.701	6.517	1.669	12.661	0.131	0.289
2	7	6.069	4.228	0.525	0.607	1.778	4.185	0.152	1.027
2	8	7.884	5.322	0.592	0.156	2.079	3.300	0.361	0.433
3	1	6.990	3.608	0.662	2.821	0.795	3.325	0.082	1.128
3	2	6.973	4.666	0.497	2.022	0.907	3.585	0.033	0.812
3	3	7.023	5.029	0.461	1.171	0.817	8.700	0.234	2.690
3	5	10.823	7.938	0.416	1.820	0.863	12.227	0.081	1.810
3	7	5.868	6.040	0.056	0.764	1.475	7.669	0.160	2.997
3	8	7.551	8.211	0.172	8.998	3.936	14.645	0.848	0.270
4	7	8.566	9.159	0.143	11.649	3.837	23.942	0.451	2.510
4	8	8.473	8.695	0.055	13.062	4.210	26.263	0.410	3.403
5	1	9.337	4.422	0.743	5.497	0.566	0.438	0.049	0.412
5	2	9.693	5.326	0.658	2.605	1.017	3.979	0.013	0.487
5	3	9.358	5.667	0.597	6.565	0.364	4.280	0.163	1.722
5	4	8.039	4.246	0.682	1.471	0.870	2.226	0.017	0.017
5	5	9.805	4.021	0.823	6.092	0.663	1.563	0.073	0.994
5	7	11.393	12.146	0.116	0.227	1.639	14.239	0.089	1.478
5	8	10.259	7.074	0.805	6.049	2.715	5.467	0.556	2.852
7	6	6.676	0.249	1.666	22.382	7.536	35.607	4.225	8.213
7	7	8.892	4.361	0.680	3.091	1.055	6.099	0.030	1.243
7	8	7.921	3.370	0.800	2.921	1.170	4.888	0.050	1.329
8	7	7.418	2.463	0.884	2.790	1.174	1.974	0.091	0.652
8	8	5.410	2.115	0.829	2.342	1.060	1.684	0.023	0.854

1: Car/Van/Jeep, 2: Tempo/Auto Rickshaw, 3: LCV, 4: Bus/Truck,
5: Motorised Two Wheelers, 6: Push Cart/ADV, 7: Bicycle, 8: Cycle Rickshaw

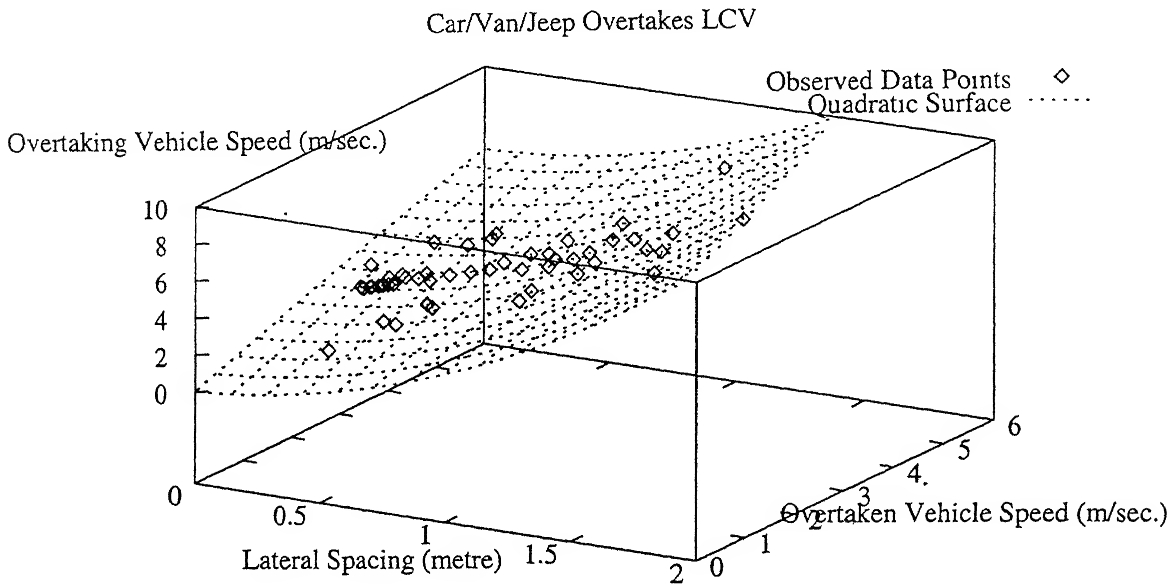


Figure 5.31: Overtaking Speed Polynomials for Car/Van/Jeep Overtakes LCV (Quadratic Surface)

- Lateral spacing maintained from the fixed objects

Lateral spacing was recorded only for those vehicles which were moving close to the road side objects. The observed data indicates that the lateral spacing from the median depends upon type and speed of the vehicle (Figures 5.32-5.34). Faster vehicles tend to maintain more lateral clearance. To estimate the safe lateral clearance from the physical barriers, following two relationships are established:

$$l_{spb} = a_0 + a_1 v \tag{5.24}$$

$$l_{spb} = a_2 + a_3 v + a_4 v^2 \tag{5.25}$$

where l_{spb}	=	Safe lateral spacing required by the vehicles from physical barriers
v	=	Speed of the vehicle
$a_1, \ldots\ldots a_4$	=	Coefficients

The estimated coefficients for the above two relationships are presented in Table 5.16 for all the eight vehicle groups. The fitted polynomials for some of the vehicle groups are shown in Figures 5.33 to 5.34. The second order polynomial gives a slightly better fit than

the linear relationship. As the lateral spacing from the physical barriers is just one of t decision parameters for overtaking/yielding process, therefore, only simple linear relationsl is adopted in the simulation model.

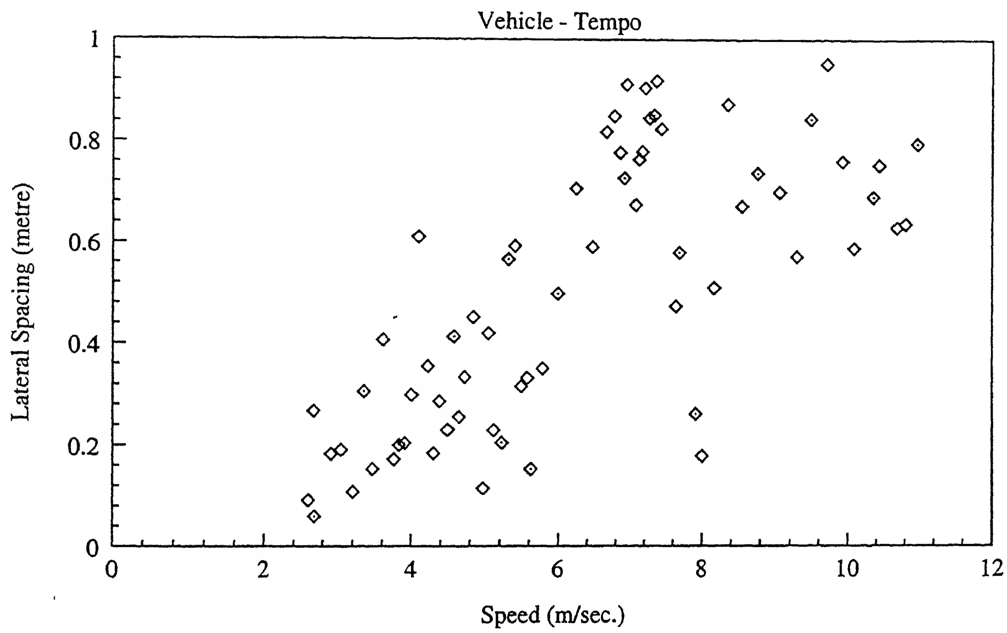


Figure 5.32: Observed Lateral Clearance for Tempo from Median

5.6.4 Space Headway Distributions and Their Parameters

When a vehicle catches up a slower vehicle and is unable to perform the flying overtaking, it is said to be in the "constrained mode" with its speed continuously reducing to that of the vehicle ahead. When the rear vehicle is moving at the speed of the vehicle ahead, then it maintains a longitudinal spacing defined as tail length. From the start of constrained mode, speed of vehicle is continuously changing and it has to maintain safe longitudinal spacing. In simulation model, the estimation of this longitudinal space headway is to be used for modelling the behaviour of vehicle in constrained situation.

Data for the longitudinal space headways for the constrained vehicles is extracted from the video images. This data includes:

- Type of constrained vehicle
- Speed of the constrained vehicle

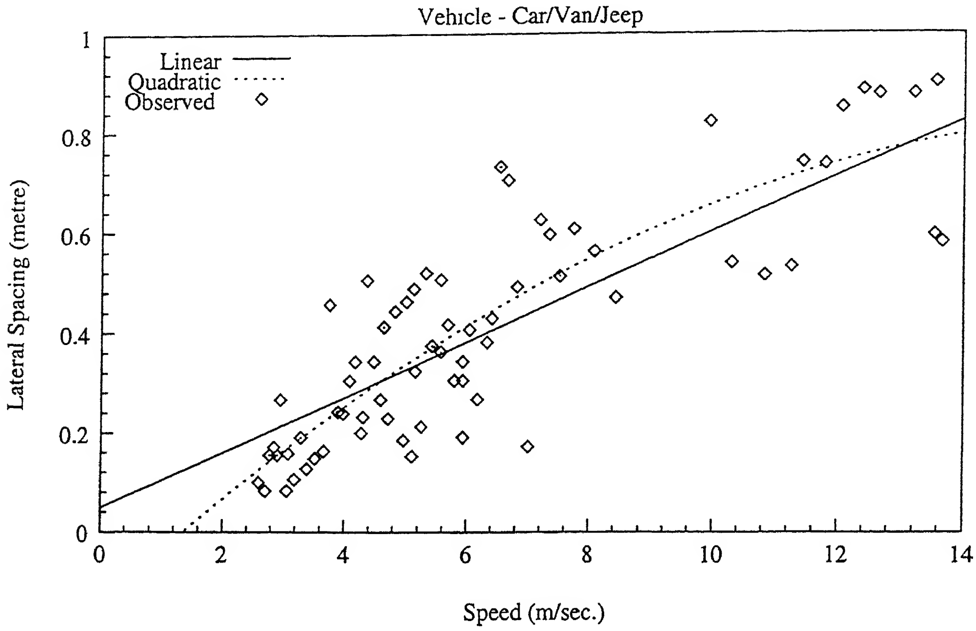


Figure 5.33: Relationships for Safe Lateral Clearance of Motorised Two Wheelers from Median

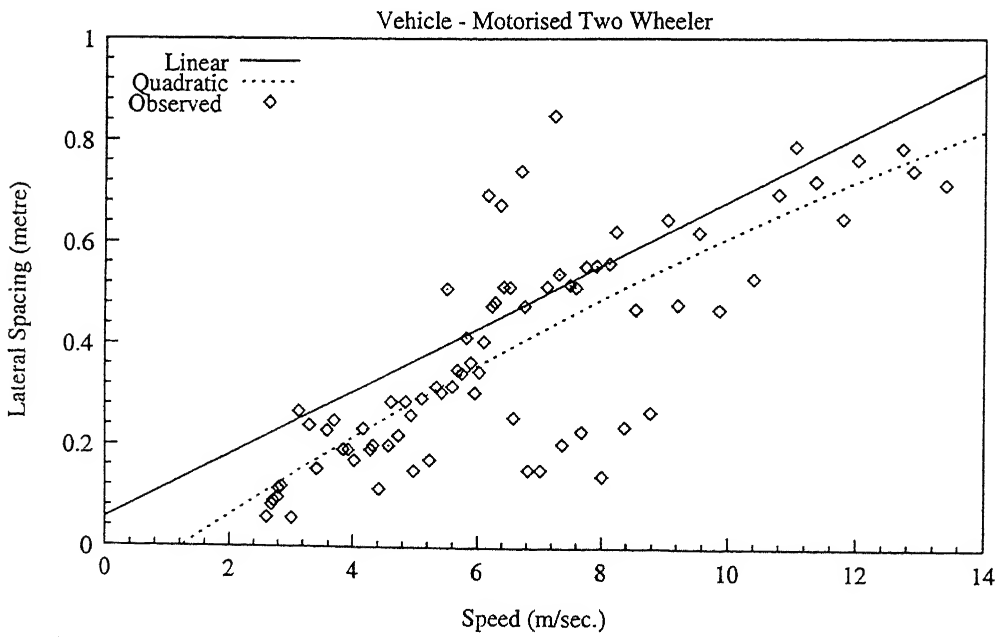


Figure 5.34: Relationships for Safe Lateral Clearance of Bicycle from Median

where sp = longitudinal spacing maintained by rear constrained vehicle
V_{fr} = speed of front vehicle
V_{re} = speed of rear vehicle
a_1, a_2 = coefficients

The first component of the above relationship indicates the minimum longitudinal spacing, that is to be maintained when following vehicle and vehicle ahead are moving at the same speed. The second component is due to higher speed of rear vehicle. The coefficients are estimated for different feasible combinations and are presented in Table 5.17.

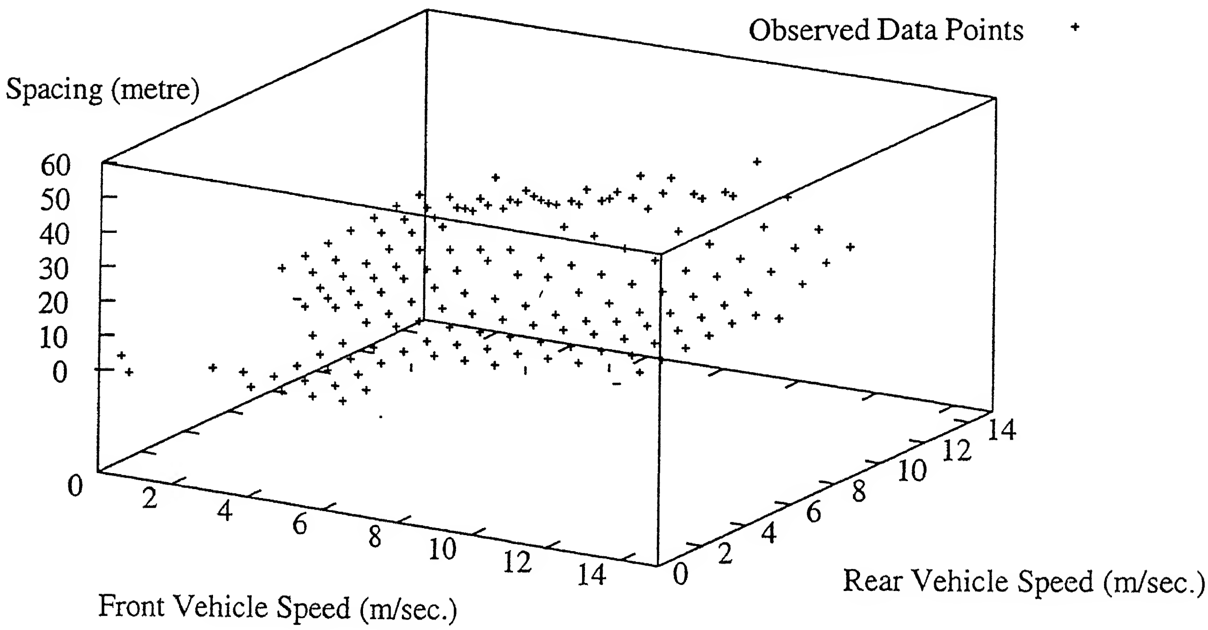


Figure 5.35: Observed Longitudinal Spacings for Car Group Following Car Group

5.7 POWER MASS RATIO DISTRIBUTIONS FROM OTHER STUDIES

The model involves estimation of the power mass ratio, coefficient of rolling and air resistances. CRRI (CRRI, 1994) conducted detailed experiments to estimate these parameters and these are adopted in this study.

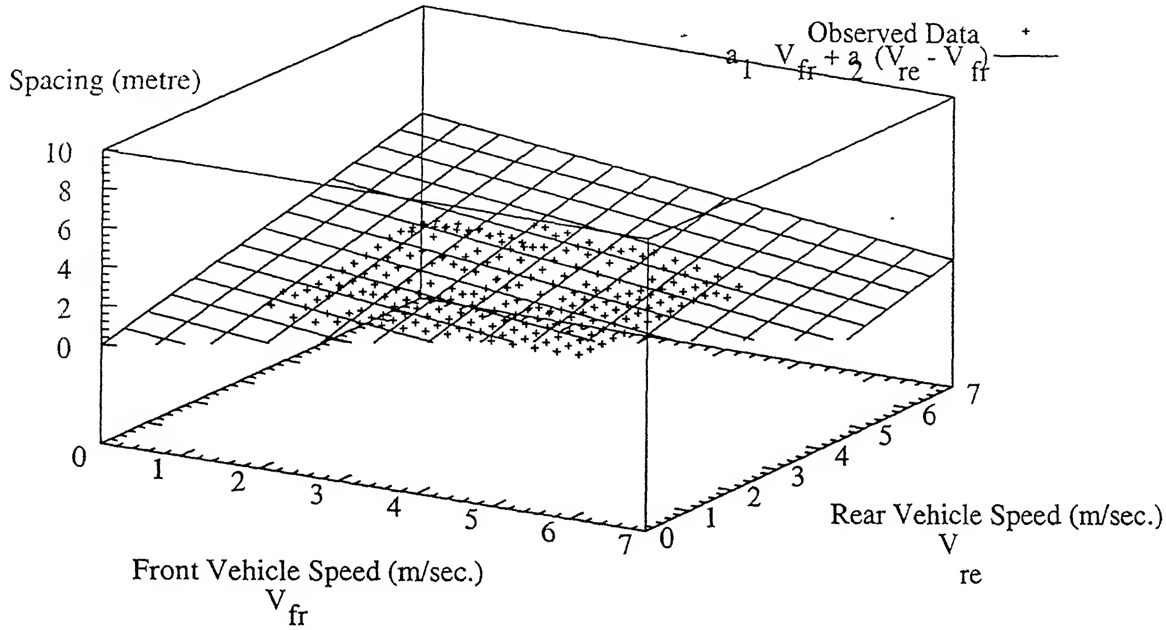


Figure 5.36: Space Headway Relation for Bicycle Following Bicycle

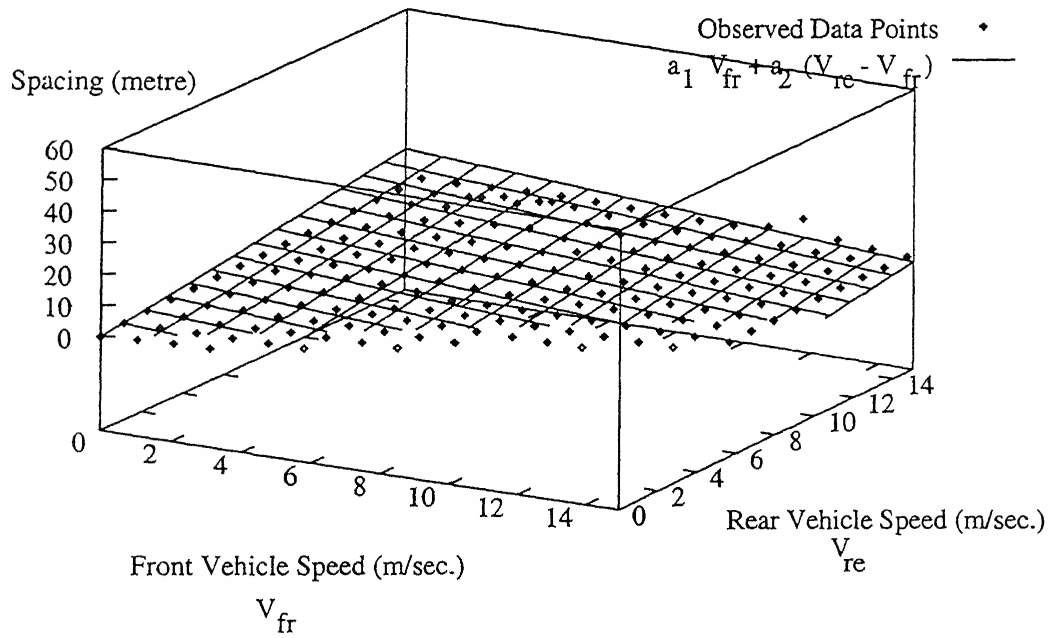


Figure 5.37: Space Headway Relation for Motorised Two Wheeler Group Following Motorised Two Wheeler Group

Table 5.17: Coefficients of Space Headway Polynomials for Different Vehicle Combinations

Front Vehicle Group	Rear Vehicle Group	a_1	a_2
1	1	0.252	3.709
1	2	0.187	3.919
1	3	0.307	3.477
1	5	0.208	2.847
2	1	0.465	2.467
2	2	0.251	1.178
2	3	0.470	2.313
2	5	0.233	2.073
3	1	0.240	3.694
3	2	0.312	2.023
3	3	0.325	3.239
3	5	0.540	1.025
5	1	0.573	1.375
5	2	0.353	1.548
5	3	0.485	1.826
5	5	0.301	1.003
7	2	0.246	0.598
7	5	0.138	0.470
7	7	0.222	0.644
7	8	0.218	0.631
8	1	0.093	1.251
8	2	0.136	0.871
8	3	0.099	1.241
8	5	0.293	0.394
8	7	0.201	0.783
8	8	0.251	1.178

1: Car/Van/Jeep, 2: Tempo, 3: LCV,
4; Bus, 5; Motorised Two Wheeler,
6: Push Cart/ADV, 7: Bicycle
8: Cycle Rickshaw

5.7.1 Rolling Resistance Experiment

The rolling resistance experiment has been performed by running the vehicle at a specified speed and switching off the Engine (in neutral gear) and allowing the vehicle to coast down to a stop. The field study was conducted to collect the data pertaining to the speed of the vehicle, the distance traveled while coasting down and the time required by the test vehicle. Table 5.18 presents the coefficients of rolling resistance (C_r) and coefficients of aerodynamic drag (air resistance) as derived from this experiment.

Table 5.18: Summary of Rolling Resistance and Aerodynamic Drag Coefficients

Vehicle type	Mass (kg)	Projected frontal area (sq.m.)	Coefficient of Rolling resistance	Coefficient of Aerodynamic Drag
Jeep	1200	2.38	0.012	0.90
Maruti Van	1050	2.29	0.010	0.68
Maruti Gypsy	1115	2.79	0.010	0.85
Fiat	1065	1.63	0.010	0.70
Ambassador	1365	2.15	0.011	0.60
Contessa	1340	2.33	0.014	0.30
Truck	6120	5.37	0.013	0.92

Source: C.R.R.I. (July, 1994), "Status Report:Development and Application of Traffic Simulation Models, New Delhi.

5.7.2 Power Mass Ratio Study

The required data has been collected to determine the mean used power mass ratio distribution of different types of motorised vehicles on three sites having different roughness levels. The collected data includes spot speeds at both ends of the section, journey time, difference in elevation, frontal area of vehicles, and distance between the points. The following relation is used to determine the power mass ratio:

$$p = \frac{V_t^2 - V_0^2}{2.0t} + \frac{gh}{t} + \frac{C_a A S^3}{mt^3} + \frac{C_r S}{t} \tag{5.28}$$

where p = power mass ratio
V_0 = Speed at time 0 ($m/sec.$)
V_t = Speed at time t ($m/sec.$)
g = Acceleration due to gravity ($\frac{m}{sec^2}$)
h = Difference of elevation between two points (m)
A = Frontal Area of the vehicle (m^2)
S = Distance between the two points (m)
C_a = Coefficient of aerodynamic drag
C_r = Coefficient of rolling resistance

The coefficient of air and rolling resistance obtained through rolling resistance experiments were taken into account while determining power to mass ratio as these consume part of tractive effort. The estimated cumulative distribution of power mass ratio for different vehicles are presented in Table 5.19.

5.8 SUMMARY

For successful development of the simulation model for heterogeneous traffic, the various phases for which data are required include: free speed study, time headway study, space headway study for constrained flow, lateral space study (overtaking/yielding manoeuvers), lateral space study from physical barriers, and calibration/validation of model.

It is planned to collect data on a major arterial of the Kanpur city. It is four lane wide with centrally raised median. On various sections of this road, traffic volume is of the order of 1600-3000 vph during peak periods. Two sections on the road are identified for data recordings. Free speed of motorised vehicles are recorded by Radar speedometer located at three different locations. Recording was done for 16 hours on two days. Video recording of traffic flow was done for a seven hour duration, which covered both peak and off peak periods with flow varying between 1600-3000 vph in each direction. In all data for about 25000 vehicles were recorded.

For traffic flow studies, the relevant information is extracted from the video recordings. Information for a vehicle relates to its longitudinal and lateral positions at a particular time. Spot speed of a vehicle can be obtained from the longitudinal positions of the vehicle at two closely spaced time intervals. It is planned to record the image size of the vehicle at appropriate times and then estimate the position of the vehicle. Due to problems in recording and extraction, the recorded vehicle image size may not be very accurate. So a detailed calibration of distance-image size relationships for different vehicle types.

Time headway analysis is done for six data sets, each of one hour duration. For the observed time headways, three composite headway distributions considered are: Schuhl,

Table 5.19: Percentage Cumulative Frequency of Power-Mass Ratio for Different Vehicles

Power Mass Ratio	Cumulative Frequency in Percent						
	AMB.	FIAT	MARUTI CAR	JEEP	M.VAN	BUS	TRUCK
2.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.0	0.00	0.00	0.00	0.00	1.54	0.00	0.00
3.5	0.00	0.00	2.65	2.78	4.62	0.00	0.00
4.0	0.00	0.00	5.31	6.94	8.47	0.00	0.00
4.5	0.00	0.00	11.50	11.11	12.31	0.00	0.00
5.0	0.00	0.00	23.89	19.44	20.77	0.00	0.00
5.5	0.00	0.00	30.09	30.56	26.15	0.00	0.00
6.0	0.00	0.00	39.82	38.89	42.31	0.00	0.68
6.5	1.16	0.00	43.36	58.33	50.0	0.00	8.11
7.0	5.81	0.00	47.79	66.67	56.92	0.00	15.54
7.5	9.30	0.00	53.98	68.05	62.31	0.00	31.76
8.0	13.95	1.27	64.60	69.44	68.46	0.00	39.86
8.5	17.44	50.65	70.80	73.61	71.54	0.76	53.38
9.0	25.28	08.86	76.99	77.78	75.38	1.53	62.16
9.5	40.70	13.92	83.19	79.86	78.46	7.63	69.59
10.0	48.84	15.19	88.50	81.94	83.85	9.16	81.08
10.5	60.47	21.52	92.04	84.03	90.00	15.27	84.46
11.0	67.44	27.85	93.81	86.11	92.31	26.72	87.84
11.5	72.09	41.77	94.69	87.50	93.85	35.11	92.57
12.0	80.23	45.57	97.35	88.89	96.15	51.55	95.95
12.5	86.05	50.63	97.79	89.81	97.69	56.49	97.97
13.0	90.70	56.96	98.23	90.74	100.00	67.94	99.32
13.5	95.35	63.29	98.45	91.67	100.00	71.76	99.66
14.0	97.67	70.89	98.68	94.44	100.00	76.34	100.00
14.5	98.84	72.15	98.89	95.37	100.00	83.21	100.00
15.0	100.00	78.48	99.12	96.29	100.00	88.55	100.00
15.5	100.00	80.38	100.00	97.22	100.00	93.13	100.00
16.0	100.00	82.28	100.00	100.00	100.00	96.18	100.00
16.5	100.00	83.54	100.00	100.00	100.00	100.00	100.00
17.0	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Source: C.R.R.I. (July, 1994), "Status Report:Development and Application of Traffic Simulation Models, New Delhi.

Modified-Schuhl (time headways of motorised and non-motorised vehicles are segregated), and Dawson composite headway distribution. Goodness of fit tested by K-S test confirm that Schuhl and Modified-Schuhl distributions describe the observed time headways. For the observed free speed data, Normal distributions were fitted for different vehicles type.

Recorded video data was analysed to extract the information with respect to interacting vehicles. It is observed that each vehicle maintains a certain minimum clearance to avoid lateral collision. However, as the speed of the vehicle increases, it has a tendency to maintain higher lateral spacing. The recorded data set is used to estimate the minimum, maximum, and distribution of lateral clearances for different vehicle types. The probability of overtaking and yielding in a situation depends upon the available lateral space. The probability of overtaking varies linearly with the available lateral space subject to constraint of minimum and maximum lateral space of the relevant vehicle group.

Lateral space study data for different combinations is analysed to estimate the speed of overtaking vehicles when passing by the side of vehicle being overtaken. It is observed that the overtaking vehicle speed increases with lateral spacing and also depends upon the overtaken vehicle speed. Appropriate relations are established.

Information of lateral spacing from the road side objects was extracted from video data for different types of vehicles. In all about 400 observations of this lateral spacing are analysed. To estimate the safe lateral clearance from physical barriers, two relationships are established.

Longitudinal spacing for the constrained vehicle depends upon type of interacting vehicles. Data for about 20-40 observations is extracted for each of the feasible combination. For different combinations of overtaking and overtaken vehicle groups, minimum and maximum values of inter-vehicular lateral spacing are observed during lateral space study. Probabilistic relations are established for overtaking/yielding decisions.

Chapter 6

CALIBRATION OF SIMULATION MODEL

6.1 GENERAL

Before using the traffic simulation model for policy experiments, it is imperative to test the validity of the model in replicating the system behaviour for traffic flows other than that used for calibration. It has been rightly stated by Naylor and Finger (1967), "The model can be used to simulate future conditions only after it has been validated and found to be a reasonable representation of the actual system under study". Martin (1968) described validation as a process of examining whether a desired accuracy or correspondence exists between the real life system and the model or not. Therefore, a valid model, mathematically and logically, approximates the functional system, operation, concept or phenomenon that are modelled.

Before defining the validation it has to made explicit that what are the parts which are to be validated. Conceptual model is to be first validated, intermingled and correlated with model implementation. Conceptual model is obviously a structure from which model is implemented as it consists of rational and clear version of the model, where real world phenomenon are carefully observed and model concepts are evolved. There after implementation of explicit model can be worked out on computer to achieve the required outputs. Thus, the first and foremost thing in the validation is to check the process of transition/transformation from real world phenomenon to conceptual model. Initially this job of conceptual model validation is obviously subjective and is based on human discriminating and judging capability.

According to Martin (1968) the logical flow chart is validated by comparison with the conceptual model, programme flow chart with the logical flow chart, computer program by comparison with the program flow chart. These steps are taken in a sequential process for

validation of computer simulation model. Here the sample problems are used. In this way sample problems can be developed by simple, suitable and artificial inputs. Thus necessary checking is feasible by comparing model outputs with sample calculation independent of model implementation. Further, according to Pyne(1982), output should be reasonably close to reference data (field data). As per Bulgron(1982), validation of simulation study is a continuous process and most useful and valid models are those that most closely emulate interactions, and cause and effect relationship of the system.

6.2 MODEL VALIDATION - AN OVERVIEW

Formulation of a model involves the definition of a structure and a set of parameters. Validation involves the verification that the structure is correct and the parameter estimates are reasonable. Generally the validation of the model is based on the agreement between throughput or output of the model with the available information. The better the agreement, the better is the validity of the model. The validation judges the correctness of the model and the various submodels that are involved in framing the model.

6.2.1 Validity of Programme Logics through Animation of Simulated Traffic Flow

While developing or modifying the logic of the various submodels, it is desirable to study clearly the effect of model changes. Since it is not convenient to fully comprehend the working of the different procedures in the program system, the animation of the traffic flow process has helped to enhance the understanding of the logics and make decisions to speed up the design process. As the simulation outputs are lengthy and difficult to interpret, the three dimensional animation of simulated traffic flow has helped to check the validity of program system.

6.2.2 Calibration of Simulation Model

It is necessary to calibrate the simulation model to see that it replicates real life urban heterogeneous traffic situation. Ideal simulation model is that which gives such outputs which are in agreement with real life data, but at the first instance this rarely happens. In the absence of synchronization different steps are taken at submodel stages on which/from which final simulation model is derived or is based. For obtaining the near ideal situation, parameters adopted for development of various submodels are changed to make submodels

near to real life situation in their respective aspects and thereby the ultimate simulation model is brought to real life situation. This whole process is known as "calibration of simulation model" (CRRI, 1996).

In calibration, parameters of the components of simulation model are estimated and adjusted to closely fit the simulated output with field data. The calibrated parameters are then maintained for validation and further experimental design.

6.2.3 Overall Model Validation

Overall validation of the simulation model is a test of how well the simulation model has been assembled into realistic structure of the system. This is a highly important phase in the development of traffic simulation model. Only after successful validation, production runs for different policy measures can be made.

6.3 CALIBRATION PROCESS

The formulated traffic simulation model consists of a series of sub-models. The realistic estimate of various parameters and decision thresholds is attempted in the calibration process. The different parameters, decision thresholds and performance measures that need to be calibrated in various submodels are given below:

Traffic Generation Model

- Vehicle type
- Entry time
- Free speed
- Entry speed
- Lateral position at entry
- Power mass ratio
- Rolling and air resistance coefficients

Traffic Interaction Model

(i) Longitudinal space for vehicle interaction
   - Tail length
   - Head length

(ii) Lateral space for vehicle movements

- Inter-vehicular lateral space
- Lateral space from physical barriers

(iii) Search areas to study vehicle interactions

- Frontal area
- Left frontal area
- Right frontal area
- Rear area
- Left rear area
- Right rear area

(iv) Constrained flow logic

- Estimation of speed of the constrained vehicle as per available longitudinal space

(v) Overtaking/yielding flow process

- Decision point for flying overtaking (longitudinal space with respect to vehicle ahead)
- Probability of overtaking/yielding
  * Free speed criteria
  * Lateral spacing criteria
- Performance measures for overtaking
  * Estimation of overtaking speed

Some submodels require calibration against the observed data. It is also necessary to calibrate the values of some parameters and decision thresholds in the light of simulation results. Three sequential stages of the calibration process as adopted in this study are:

- **Stage I** - Estimation of some parameters based on analysis of direct field measurements.
- **Stage II** - Estimation of some parameters and decision thresholds based on the observations and inferences of this and other studies.
- **Stage III** - Calibration of parameters for decision process and various performance measures based on experimental simulation runs.

6.4 TRAFFIC INPUT FOR SIMULATION EXPERIMENT

Simulation run for calibration is made for an observed hourly volume of 1694 vph. The observed volumes during the 15 minute intervals are 377, 429, 462 and 426 giving peak hour

factor (PHF) of 0.917. This value of peak hour factor indicates that there are no significant variations of traffic flow within the hour.

Table 6.1: Traffic Volume and Composition of Traffic Data used for Calibration

Time Interval (minutes)		Volume
0.0-15.0		377
15.0-30.0		429
30.0-45.0		462
45.0-60.0		426
Total (vph)		1694
Vehicle Type	Volume	Proportion Percentage
Car/Van/Jeep	83	4.90
Tempo/Auto Rickshaw	228	13.45
Bus/LCV	37	2.18
Motorised Two Wheeler	304	17.95
Push Cart/ADV	5	0.29
Bicycle	819	48.35
Cycle Rickshaw	218	12.86
Non-Motorised Vehicles	1042	61.51
Motorised Vehicles	652	38.49

Traffic composition, presented in Table 6.1, indicates that traffic is highly heterogeneous dominated by non-motorised vehicles. Proportion of non-motorised vehicles (61.51 percent) is much higher than that of motorised vehicles (38.49 percent). Amongst the non-motorised vehicles, contribution of bicycle is the highest (48.35 percent). Cycle rickshaws are 12.86 percent of the total flow. Amongst the motorised vehicles, three wheelers (tempos/auto rickshaws - 13.45 percent) and two wheelers (17.95 percent) have the highest proportion. The proportion of car is only 4.90 percent of the total traffic mix and its hourly volume is 83 vph.

The distribution of entry speed (mean and standard deviation) for different vehicle types is given in Table 6.2. Mean entry speed of all non-motorised vehicles (4.35 m/sec) is less in comparison to motorised vehicles (7.16 m/sec). Amongst the non-motorised vehicles, mean entrance speed of ADV/push carts (2.18 m/sec) is the least and mean entrance speed of bicycles (4.54 m/sec) is the highest. In motorised vehicles group, mean entrance speed of car/van/jeep (8.09 m/sec) is the highest and the entrance speed of tempo/auto rickshaw (6.13 m/sec) is the least.

Table 6.2: Mean and Standard Deviation of Entry Speed for different Vehicle Groups

Vehicle Type	Entry Speed	
	Mean (m/sec.)	Standard Deviation (m/sec.)
Car/Van/Jeep	8.09	2.37
Tempo/Auto Rickshaw	6.13	1.77
Bus/LCV	6.30	2.07
Motorised Two Wheeler	7.79	2.35
Push Cart/ADV	2.18	0.46
Bicycle	4.54	0.76
Cycle Rickshaw	3.69	0.79
All Non-Motorised Vehicles	4.35	0.86
All Motorised Vehicles	7.16	2.31
All Vehicles	5.43	2.09

Mean and standard deviation of lateral position at entry for different vehicle groups are given in Table 6.3. It is clear from the table that non-motorised vehicles move close to left side of the road and most of the motorised vehicles occupy right part of the road.

Table 6.3: Mean and Standard Deviation of Lateral Position (from Left Side of the Road) at Entry for Different Vehicle Groups

Vehicle Type	Lateral Position at Entry	
	Mean (metre)	Standard Deviation (metre)
Car/Van/Jeep	5.84	1.10
Tempo/Auto Rickshaw	5.07	0.78
Bus/LCV	5.66	0.82
Motorised Two Wheeler	5.24	0.89
Push Cart/ADV	3.26	0.72
Bicycle	3.52	0.76
Cycle Rickshaw	3.71	0.85

6.5 CALIBRATION OF TRAFFIC GENERATION MODEL

Traffic generation model generates the vehicle characteristics and other attributes of the traffic and is an input for the simulation model. Traffic parameters of interest are:

- Vehicle identification number
- Vehicle type
- Free speed
- Power mass ratio
- Rolling resistance and air resistance coefficients
- Entry time
- Entry speed
- Longitudinal position at entry
- Lateral position at entry

The various parameters of traffic are generated in following two ways:

1. From observed field traffic for simulation runs of calibration and validation.
2. Generate traffic for established distribution of various parameters.

Various distributions and other estimated parameters, as discussed in Chapter 5, are used for generation. To judge the validity of generated traffic data, statistics of free speed and power mass ratio for generated traffic are compared with the observed statistics. Generated and observed cumulative frequency distribution of free speed and power mass ratio are shown in Figures 6.1 to 6.4 for some vehicle type. The nature of distributions are quite identical justifying the validity of traffic generated input for the simulation runs.

Entry Speed

For the observed traffic, the entry speed of the vehicles is directly recorded. But in case of generated traffic for simulation runs, a vehicle is to be assigned an entry speed. Entry speed of the vehicles in a traffic stream is a function of

- Free Speed

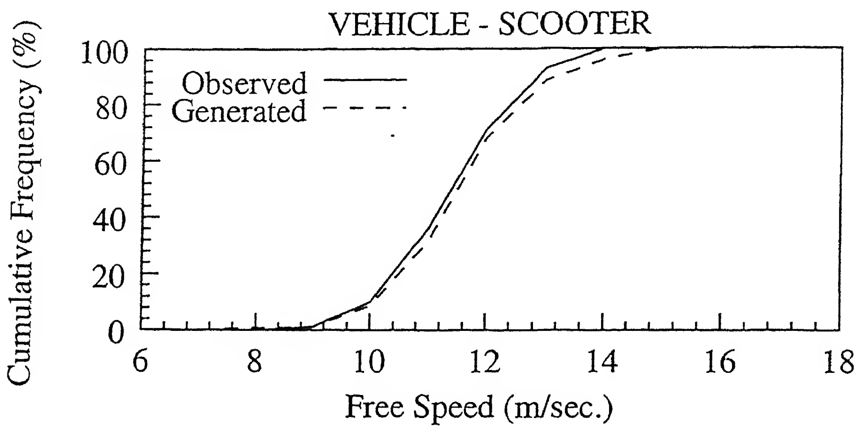


Figure 6.1: Comparison of Observed and Generated Free Speed Distributions for Scooter

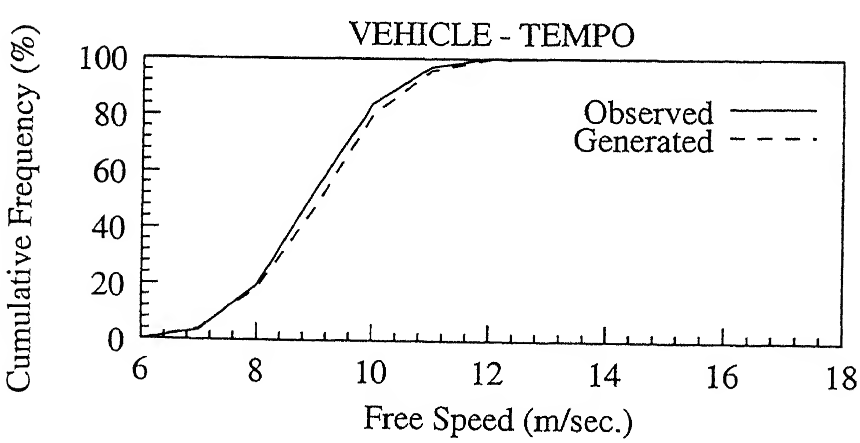


Figure 6.2: Comparison of Observed and Generated Free Speed Distributions for Tempo

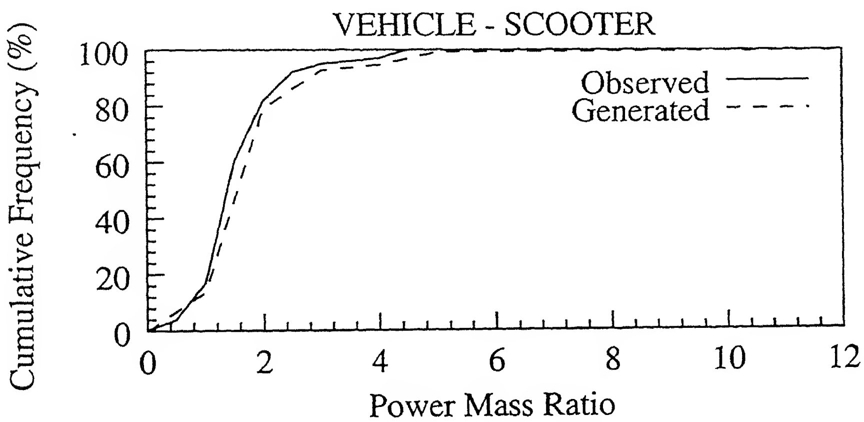


Figure 6.3: Comparison of Observed and Generated Power Mass Ratio Distributions for Scooter

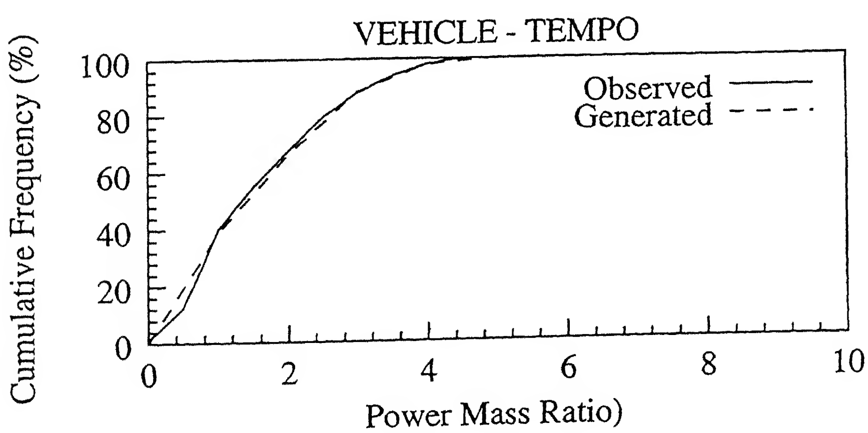


Figure 6.4: Comparison of Observed and Generated Power Mass Ratio Distributions for Tempo

- Traffic composition
- Flow rate

Entry speed can be represented as given in Equation 6.1 .

$$v_{ent} = ent\_sp\_fac * v_{fr} \tag{6.1}$$

where ent_sp_fac = modification factor for converting free speed into entry speed.
At lower traffic flow rates, modification factor has been taken as 0.80 and this value is further decreased to 0.50 at high traffic flow rates. It is assumed that modification factor varies linearly with flow rates. To realistically assign the traffic input to the simulated road section, an additional warm up section of adequate length is included before the actual road stretch. This warm up section helps to eliminate the effect of transient state and to quantify other characteristics which affect entry speed.

Lateral Position

To assign the lateral position of the vehicle at entry frequency distribution of lateral position for different vehicle types are recorded for two traffic flow levels of 1600 vph and 2400 vph. These distributions are used to generate lateral position of vehicle at entry to the warm up zone. Lateral position depends upon many factors and it is very difficult to quantify the contribution of each factor. However, warming up zone helps to get a realistic distribution of lateral positions.

6.6 CALIBRATION OF TRAFFIC INTERACTION MODEL

6.6.1 Longitudinal Space for Vehicle Movement

When a vehicle (B) is following, it maintains a certain spacing with respect to the front vehicle (A). This spacing depends upon the speed, deceleration rate and length of the vehicle and a certain minimum time headway (t_h). A vehicle will maintain this minimum spacing with reference to the vehicle in rear. This spacing is designated as tail length of the vehicle. For determination of tail length, a certain minimum spacing is specified as the lower bound for the tail length. In the present model tail length is defined as

$$\text{taillength}_A = max(m_t, V_A * t_h) \tag{6.2}$$

where taillength_A = tail length of vehicle A
V_A = speed of vehicle A
m_t = minimum tail length
t_h = minimum time headway

Some of the earlier researchers (Kulkarni, 1981; Bandyophadyay, 1984; Chelapathi,1987) have taken value of minimum time headway between 1.0-2.0 seconds for calculating required tail length. Most of these studies are confined to rural road stretch having predominant contribution of four wheeled motorised vehicles. But the present case of urban heterogeneous traffic which has high flow rates and large proportion of non-motorised vehicles, minimum time headway of 1.0 second has been considered for all type of vehicles to calculate tail length.

The distance traveled by rear vehicle B in reducing its speed from V_B to V_A is designated as head length of the vehicle. Head length of vehicle B is defined as

$$\text{headlength}_B = \frac{V_B^2 - V_A^2}{2 * Dec}, \qquad for \;\; V_B > V_A \tag{6.3}$$

where headlength_B = Head length of vehicle B
V_B = speed of following (rear) vehicle
Dec = Maximum deceleration rate of vehicle

The value of maximum deceleration rate adopted is 2.0 m/sec^2, which is based on the road traffic simulation studies conducted on Indian roads (Bandyopadhyay, 1984).

6.6.2 Lateral Space for Vehicle Movement

It is assumed that lateral spacing required by a vehicle varies linearly between the minimum and maximum value of observed lateral spacings. Required lateral spacing at an instant of time also depends upon the speed of the vehicle. Lateral spacing can be defined as

$$\text{lateral space} = fac * [\frac{cu\_sp - min\_sp}{max\_sp - min\_sp}(max\_ls - min\_ls) + min\_ls] \tag{6.4}$$

where fac = adjustment factor for lateral space
cu_sp = velocity of the vehicle
min_ls = minimum lateral spacing of a vehicle group;
max_ls = maximum lateral spacing of a vehicle group;
min_sp = minimum speed of a vehicle group;
max_sp = maximum speed of a vehicle group

Minimum speed of the vehicle is taken to be zero, i.e., vehicle is stopped. Maximum speed of the vehicle is taken to be the probable maximum free speed of vehicle type. Prob-

able maximum speed can be mathematically represented as

$$v_{pm} = \mu_{fr} + 3.0\sigma_{fr} \tag{6.5}$$

where v_{pm} = probable maximum speed;
μ_{fr} = mean free speed of vehicle type; and
σ_{fr} = standard deviation of free speeds;

Mean and standard deviation of free speeds are estimated from the field observations. Analysis of observed field data has estimated the parameters of minimum and maximum lateral space for different vehicle types. The actual lateral space maintained by a vehicle lies between these two threshold values. In the observed traffic flow, when recording the lateral spacing, a judgment is to be made about the interaction of the vehicle. When traffic flow is moderate the vehicles may have more lateral spacing and may not be actually interacting. This error of judgment may result in higher value of the maximum lateral space. The calibration of adjustment factor is done from the results of the experimental simulation runs. With the adjustment factor equal to unity, the simulated journey speeds were observed to be lower than observed ones. Trial runs were made with different values of adjustment factor ranging from 0.4-1.0. The comparison of results helped in fixing the value of adjustment factor as 0.7.

6.6.3 Lateral Space from Physical Barriers

A vehicle attempts to maintain safe lateral clearance from physical barriers. To estimate the safe lateral clearance from the physical barriers, following two relationships are established from field observations :

$$l_{spb} = a_0 + a_1 v \tag{6.6}$$

$$l_{spb} = a_2 + a_3 v + a_4 v^2 \tag{6.7}$$

where l_{psb} = Safe lateral spacing required by the vehicles from physical barriers
v = Speed of the vehicle
a_0, a_1, a_2, a_3 = Coefficients

The estimated values of coefficients (Chapter 5) are adopted without any further modification.

6.6.4 Search Areas to Study Interaction

For decision making, area under the influence of a vehicle is to be scanned. This model specifies six types of search areas.

- Ahead of the Vehicle
  - Frontal search area
  - Left frontal search area
  - Right frontal search area
- Rear of the Vehicle
  - Rear search area
  - Left rear search area
  - Right rear search area

If proper value of search length and width are chosen, then it is expected that all vehicles which are interacting with the current vehicle will be considered in the decision process.

In the present study, dynamic search area is a function of current and interacting vehicle characteristics. Search length and width can be calculated as given in Section 3.9 of Chapter 3. There is no further adjustment for search width. But there is a need to calibrate multiplying factor for search length. Multiplying factor is used to ensure that the search area does not miss the interactions. Trial runs were made for different values of multiplying factor ranging between 1.0-2.0. It is observed that there is no significant change because components of search length are calculated in a manner to take care of extreme conditions. Finally the value of multiplying factor is adopted as 2.0.

6.6.5 Constrained Flow Logic

Estimation of speed of the constrained vehicle as per available longitudinal space

When a vehicle catches up a slower vehicle and is unable to perform the flying overtaking, it is said to be in the constrained mode with its speed continuously reducing to that of the vehicle ahead. The constrained vehicle maintains a certain longitudinal space depending upon speed of the vehicle being followed. For a particular case, the longitudinal spacing depends upon the speed of the front vehicle and the difference in the speed of rear and front vehicles. It is expressed as:

$$sp = f(V_{fr}, V_{re} - V_{fr}) \tag{6.8}$$

$$sp = a_1 V_{fr} + a_2(V_{re} - V_{fr}) \tag{6.9}$$

where V_{fr} = speed of front vehicle
V_{re} = speed of rear vehicle

Coefficients of the above expressions are estimated based on the actual field observations and are presented in Chapter 5.

6.6.6 Overtaking/Yielding Flow Process

Decision point for flying overtaking

When a faster vehicle catches up a slower vehicle ahead, it has to take a decision whether to perform flying overtaking or start following. At this decision point, the probability of overtaking is estimated and vehicle is moved accordingly. The location of the decision point is with respect to its spacing from the vehicle ahead. This spacing, defined as interaction distance, is:

$$l_d = f(hl_{ovt}, tl_{ovn}) \tag{6.10}$$

Maximum threshold spacing is further modified with coefficient (mul_coff).

$$l_d = mul\_coff(hl_{ovt} + tl_{ovn}) \tag{6.11}$$

where l_d = Interaction distance, which is separation between overtaking and overtaken vehicles;
hl_{ovt} = head length of overtaking vehicle;
tl_{ovn} = tail length of overtaken vehicle;
mul_coff = multiplying coefficient.

The multiplying coefficient needs to be calibrated. The calibration of interaction distance is of great importance as at this moment, decision process gets activated. The value of the multiplying coefficient has to be greater than unity. The selection of this coefficient is made through simulation runs for the road section on which the actual observations of the traffic flow were recorded.

With value of multiplying coefficient as unity, it is observed that simulated number of overtakings are less than the observed number of overtakings. The simulated journey speeds are also less than the observed journey speeds. By increasing the value of factor, it was observed that the simulated number of overtakings increase and simulated journey speeds are also higher. Trial runs with different values of multiplying coefficient indicated that for the value of factor as 2.0, the simulated values are quite close to the observed values. For further increase of value, there is no significant difference between observed and simulated values. By adopting this value simulations are made for another level of traffic flow and

the simulated results are quite comparable to the observed ones. Hence, finally the value of multiplying factor as 2.0 is adopted.

Probability of Overtaking/Yielding

The probability of overtaking/yielding is based on following two probability values:
(a) Probability (**Prob1**) based on free speed.
(b) Probability (**Prob2**) based on inter-vehicular lateral spacing.

The probability functions are already discussed in Chapter 5. The estimation of above probabilities need calibration of parameters.

Probability (Prob1) Based on Free Speed Criteria

The probability of overtaking depends upon the difference in free speeds of overtaking and overtaken vehicles. Related studies have shown that for a certain difference in free speeds (ΔFS_{max}), all vehicles attempt to overtake if appropriate space is available. In some studies this value is taken as 25 kmph (Brodin, 1983; Brodin and Carlson, 1985; Chelapathi, 1987). For the heterogeneous urban traffic flow, where the free speeds are on the lower side, a value of ΔFS_{max} adopted is 15 kmph in this study. Whenever the ΔFS_{max} is greater than 15 kmph, probability Prob1 is maximum (=1). For the value of ΔFS_{min} (=0), there is no chance of overtaking. For difference between 0-15 kmph, probability varies linearly.

Probability (Prob2) based on inter-vehicular lateral spacing criteria

The probability of overtaking/yielding also depends upon the available lateral spacing for the vehicle. Analysis of field observations for lateral spacing maintained during overtaking have estimated the minimum and maximum lateral spacing for different vehicle group combinations (Chapter 5). These estimated values are used in the probability function. The probability of overtaking varies linearly between the estimated threshold value of minimum and maximum lateral spacing.

The final probability of overtaking in decision making is taken to be the minimum of above mentioned two probabilities (Prob1, Prob2).

$$prob = min(\text{Prob1}, \text{Prob2}) \tag{6.12}$$

Performance Measures for Overtaking - Estimation of Overtaking Speed

During the movement of vehicle in the overtaking/yielding mode, its speed is to be estimated at different time intervals. Study of the field data indicates that speed of the overtaking vehicle depends upon inter-vehicular lateral spacing and overtaken vehicle speed. Based on

the field measurements, the speed of the overtaking vehicles are estimated as follows:

$$ovt_{vel} = a_1 l_s, \tag{6.13}$$

$$ovt_{vel} = a_2 l_s + a_3 ovn_{vel}, \tag{6.14}$$

$$ovt_{vel} = a_4 l_s + a_5 ovn_{vel} + a_6 l_s^2 + a_7 ovn_{vel}^2 + a_8 l_s ovn_{vel}; \tag{6.15}$$

where ovt_{vel} = speed of overtaking vehicle
ovn_{vel} = speed of overtaken vehicle
l_s = Lateral space available on the side of during overtaking operation
$a_1, a_2, \ldots\ldots, a_8$ = coefficients for relationships

The second relationship, as given in equation 6.14, is finally adopted in the simulation model for predicting speed of overtaking vehicles.

The stages adopted in calibration of different parameters and decision thresholds, as discussed earlier, are summarised in Table 6.4.

6.7 CALIBRATION THROUGH SIMULATION RUNS

The final stage of calibration involves conduct of simulation runs. Study of the simulation results is made use of to adjust the relevant parameters to be calibrated. This stage involved following two parameters:

- Lateral space for vehicle movement (inter-vehicular lateral space).
- Decision point for flying overtaking (interaction distance).

The strategy for calibration and the final adopted values are already discussed. The experimental simulation runs are made on the road for which the field observations are available. A stretch of 100 metre length is selected and traffic is simulated for two different flow levels. The simulated journey speeds are compared with the observed values.

Traffic input to the simulation model is based on actual observed traffic. In first set of iterations, the value of interaction distance is calibrated. After fixing this value, the adjustment of lateral spacing is made in the second set of iterations.

6.7.1 Analysis of Simulation Results

Comparison of the observed and simulated values of journey speeds for different vehicle types are presented in Table 6.5. This table includes the sample size of each vehicle group, mean

Table 6.4: Stage Wise Description of Calibration Process

Calibrated parameters	Level of Calibration
Traffic Generation Model	
Free Speed	Stage I
Power Mass Ratio	Stage II
Rolling and Air Resistance	Stage II
Entry Time	Stage I
Entry Speed	Stage I
Longitudinal Position at Entry	Stage I
Lateral Position at Entry	Stage I
Longitudinal Space for Vehicle Interaction	
Head Length	Stage II
Tail Length	Stage II
Lateral Space for Vehicle Movement	
Inter-vehicular Lateral Space	Stage I, Stage III
Lateral Space from Physical Barriers	Stage I
Search Area to Study Interaction	
Frontal Search Area	Stage II
Left Frontal Search Area	Stage II
Right Frontal Search Area	Stage II
Rear Search Area	Stage II
Left Rear Search Area	Stage II
Right Rear Search Area	Stage II
Constrained Flow Logic	
Estimation of Speed of the Constrained Vehicle	Stage I
Overtaking/Yielding Flow Process	
Decision Point for Flying Overtaking	Stage III
Probability of Overtaking/Yielding	
- Free Speed Criteria	Stage II
- Lateral Spacing Criteria	Stage II
Performance for Overtaking	
-Estimation of Overtaking Speed	Stage I

Table 6.5: Comparison of Observed and Simulated Journey Speeds

Vehicle Group	Sample Size	Observed Journey Speed		Simulated Journey Speed			
				Approach I Car Following		Approach II Sp. Head. Polyn.	
		Mean (m/sec.)	St. Dev. (m/sec.)	Mean (m/sec.)	St. Dev. (m/sec.)	Mean (m/sec.)	St. Dev (m/sec.)
Car/Van/Jeep	83	8.39	1.81	8.69	2.30	9.40	2.16
Tempo/Auto Rickshaw	226	6.05	1.46	6.25	1.39	6.48	1.56
Bus/LCV	37	6.56	1.61	6.59	1.56	6.38	1.56
Motorised Two Wheeler	304	7.38	2.04	7.19	2.30	7.75	2.25
Push Cart/ADV	5	2.28	0.36	2.22	0.40	2.22	0.40
Bicycle	815	4.45	0.75	4.41	0.66	4.43	0.65
Cycle Rickshaw	217	3.77	0.80	3.91	0.55	3.95	0.51

Sp. Head. Polyn.: Space Headway Polynomial
St. Dev. Standard Deviation

and standard deviation of journey speeds for the observed and simulated data. Simulated values are for two different approaches:

Approach I: Car following model for constrained flow

Approach II: Space headway polynomials for constrained flow

Bar charts representing the mean and standard deviation of journey speeds by approach I are shown in Figures 6.5-6.6 and in Figures 6.7-6.8 by approach II. It is noted that simulated journey speed values are quite comparable with the observed values. The maximum difference in mean journey is less than 1 m/sec for fast vehicles. For approach I, the difference between the observed and simulated values are quite low whereas the differences are slightly higher for approach II. Figure 6.9 shows the comparison of observed and simulated mean journey speeds for different vehicle groups by approach I. Most of the values are quite close to the 45^o line indicating closer resemblance of observed and simulated values. Similarly Figure 6.10 shows the comparison of observed and simulated mean journey speeds for different vehicle groups by approach II. Some values are slightly away from the 45^o line indicating a higher dispersion in some cases. The distribution of the journey speeds for a few vehicle types are shown in Figures 6.11-6.14 for the observed and simulated values of approach I and approach II. The nature of the dispersion indicates that simulated values and observed values are quite close.

Only for approach II, the dispersion is more at high speeds. These comparisons indicate that approach I gives results more close to the observed values. The reason for variation in approach II may be because of limited number of data points for which space headway polynomials were established. Approach I is finally adopted for validation and simulation experiments for sensitivity analysis.

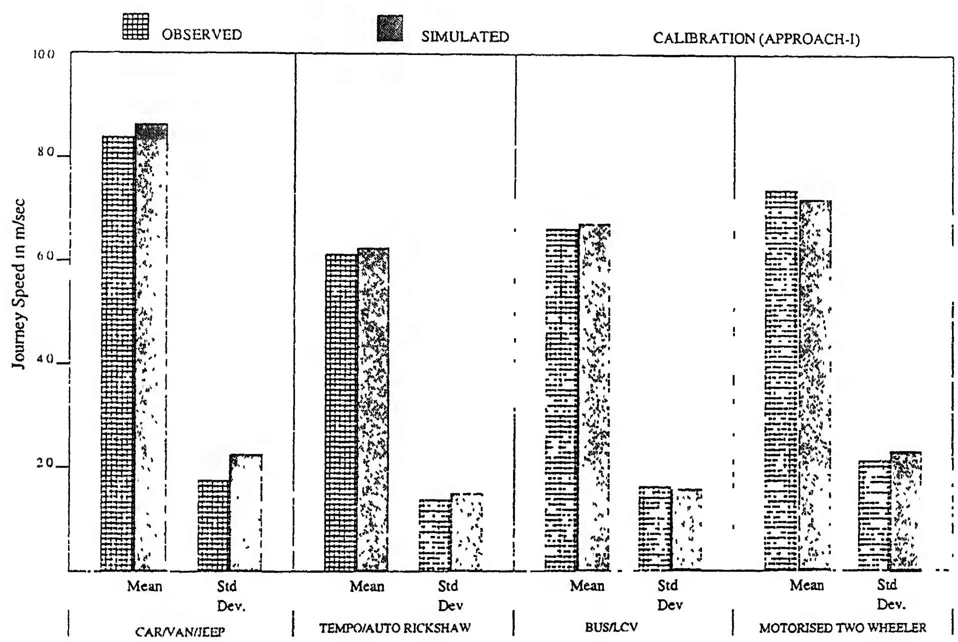


Figure 6.5: Comparison of Observed and Simulated Journey Speeds (Approach I)

6.8 SUMMARY

The formulated traffic simulation model consists of a series of sub-models. The realistic estimate of various parameters and decision thresholds is attempted in the calibration process. Some submodels require calibration against the observed data. It is also necessary to calibrate the values of some parameters and decision thresholds in the light of simulation results. Three sequential stages of the calibration process as adopted in this study are:

- **Stage I** - Estimation of some parameters based on analysis of direct field measurements.
- **Stage II** - Estimation of some parameters and decision thresholds based on the observations and inferences of this and other studies.

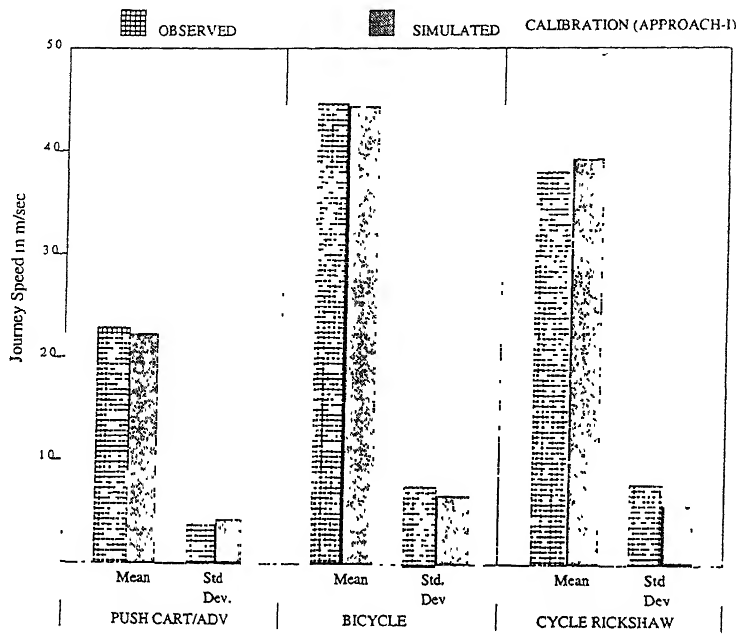


Figure 6.6: Comparison of Observed and Simulated Journey Speeds (Approach I)

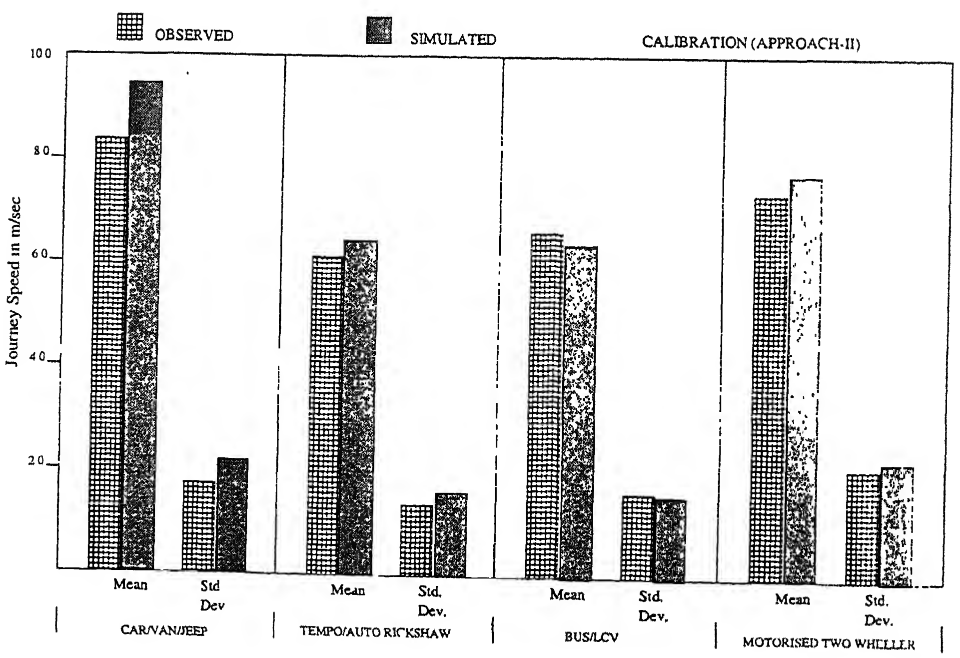


Figure 6.7: Comparison of Observed and Simulated Journey Speeds (Approach II)

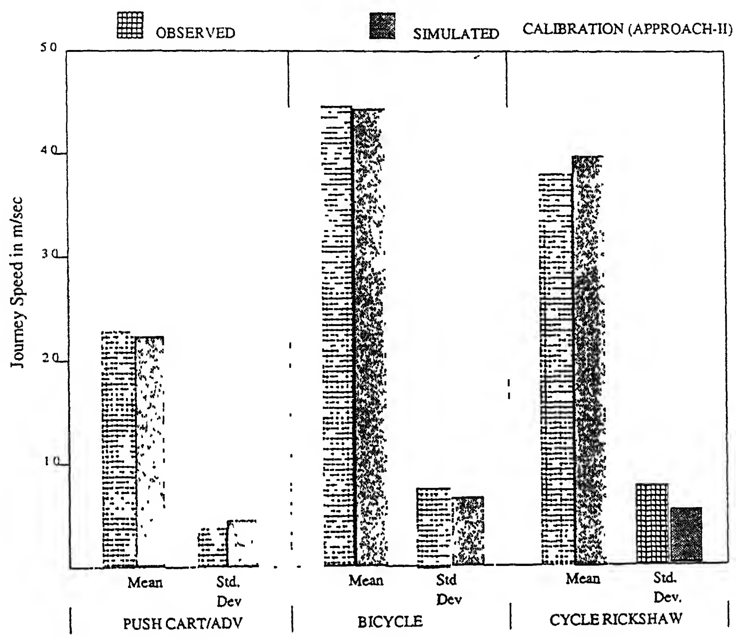


Figure 6.8: Comparison of Observed and Simulated Journey Speeds (Approach II)

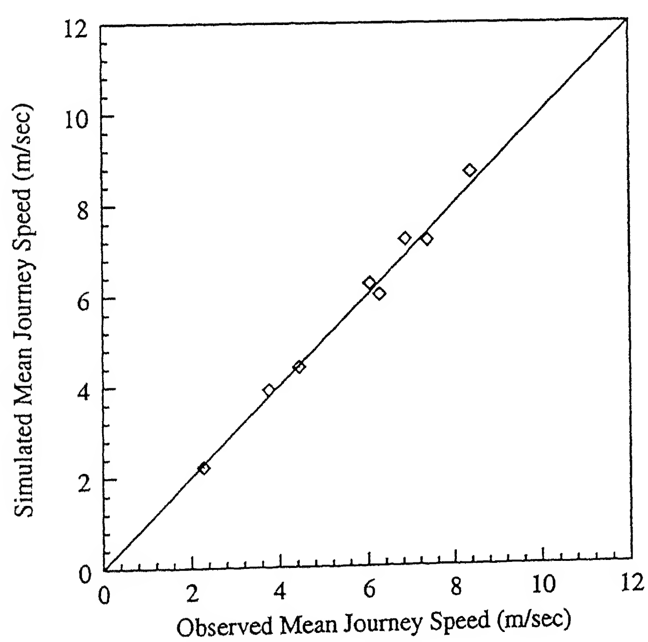


Figure 6.9: Comparison of Observed and Simulated Mean Journey Speeds (Approach I)

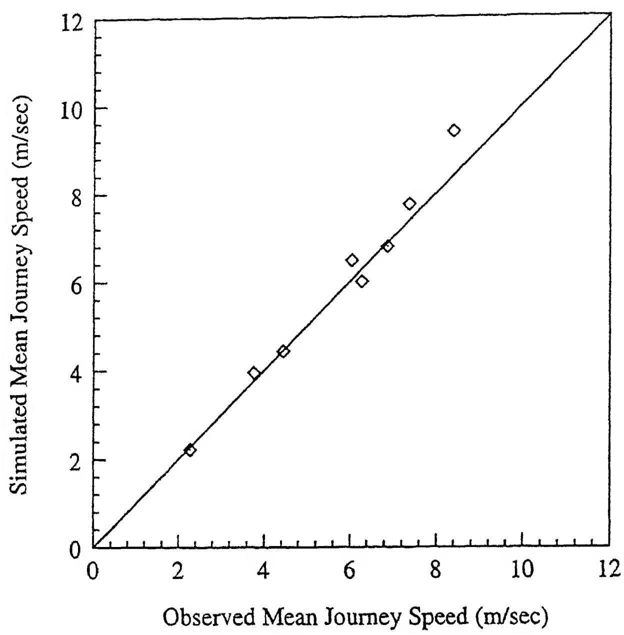


Figure 6.10: Comparison of Observed and Simulated Mean Journey Speeds (Approach II)

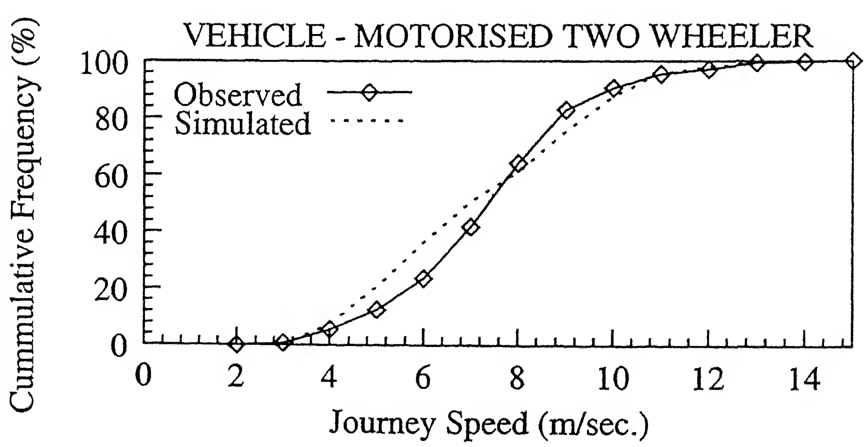


Figure 6.11: Comparison of Observed and Simulated Distributions of Journey Speed by Approach I (Motorised Two Wheeler)

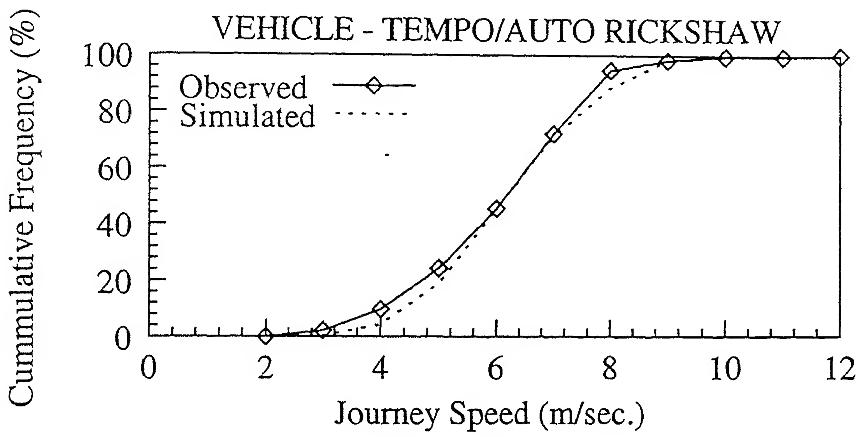


Figure 6.12: Comparison of Observed and Simulated Distributions of Journey Speed by Approach I (Tempo/Auto Rickshaw)

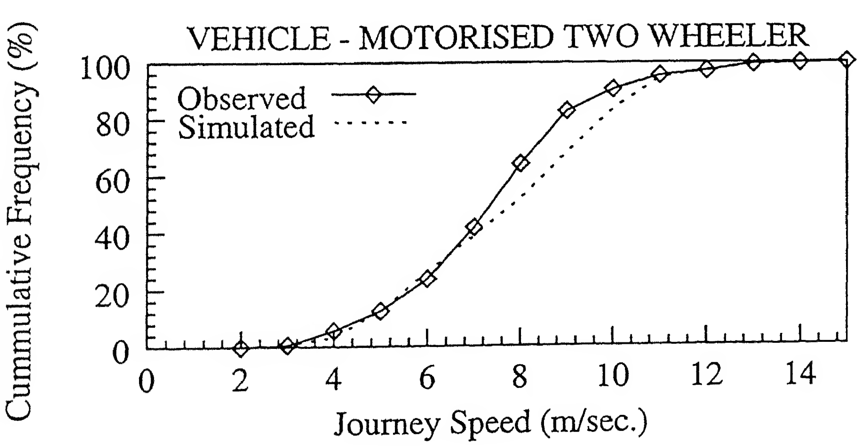


Figure 6.13: Comparison of Observed and Simulated Distributions of Journey Speed by Approach II (Motorised Two Wheeler)

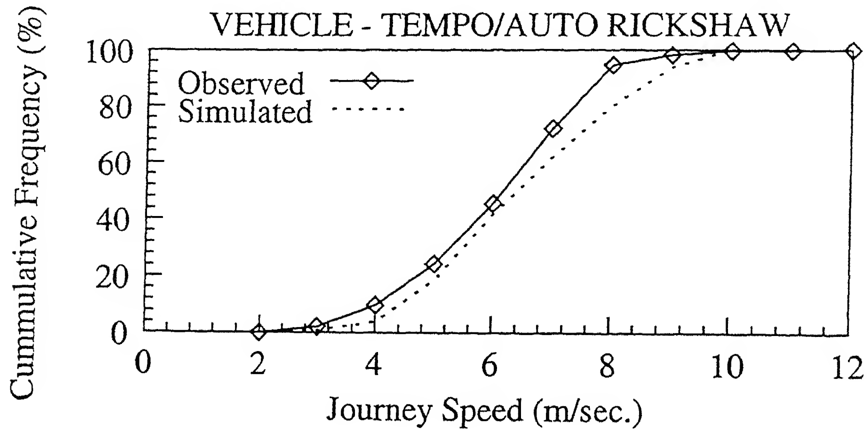


Figure 6.14: Comparison of Observed and Simulated Distributions of Journey Speed by Approach II(Tempo/Auto Rickshaw)

- **Stage III** - Calibration of parameters for decision process and various performance measures based on experimental simulation runs.

Calibration of traffic interaction model is done by fixing the value of parameters and decision thresholds of submodels. Minimum time headway of 1.0 second has been considered for all type of vehicles to calculated tail length. The value of maximum deceleration rate adopted is 2.0 m/sec^2.

Analysis of observed field data has estimated the parameters of minimum and maximum lateral space for different vehicle types. The calibration of adjustment factor for lateral space is done from the results of the simulation runs. The comparison of results helped in fixing the value of adjustment factor as 0.7.

Trial runs were made for different values of multiplying factor for search length and it ranging between 1.0-2.0. Finally the value of multiplying factor adopted is 2.0. Parameters of the longitudinal space submodel, overtaking and yielding submodels, estimation of overtaking speed polynomials are calibrated from field studies and results of previously conducted field studies.

When a faster vehicle catches up a slower vehicle ahead, it has to take a decision whether to perform flying overtaking or start following. Interaction distance for decision point is calibrated as twice the sum of head length and tail length.

The experimental simulation runs are made on the road for which the field observations are available. A stretch of 100 metre length is selected and traffic is simulated for two

different flow levels. Comparison of the observed and simulated values of journey speeds for different vehicle types are made. Simulated values are for two different approaches:

Approach I: Car following model for constrained flow and

Approach II: Space headway polynomials for constrained flow

These comparisons indicate that approach I gives results more close to the observed values. The reason for variation in approach II may be because of limited number of data points for which space headway polynomials were established. Approach I is finally adopted for validation and simulation experiments for sensitivity analysis.

Chapter 7

VALIDATION OF SIMULATION MODEL

7.1 INTRODUCTION

Formulation of a model involves the definition of a structure and a set of parameters. Validation involves the verification that the structure is correct and the parameter estimates are reasonable. Validation is done to judge the correctness of the model and the various submodels that are involved in formulating the model. The overall validation of the simulation model is a test of how well the submodels have been assembled into a realistic structure of the system.

Animation of the simulated traffic flow and different stages of calibration process have helped to formulate realistic flow logics and calibrate various parameters and decision thresholds of different submodels. The overall validation of the Simulation Model is attempted in this exercise.

7.2 MEASURES OF EFFECTIVENESS

Properties to be used as measures of effectiveness in validation have to be such that they represent the output of the whole system and can also be accurately measured in the field. These properties be such that agreement implies that the model is satisfactory and disagreement implies the model to be unsatisfactory.

The following measures of effectiveness are selected for validation:

- Distribution of journey speeds (or travel times) over the test sections for different types of vehicles. This property is of utmost importance in describing the flow characteristics.

- Distribution of time headways for different vehicle types on exit.
- Traffic density of the road stretch.
- Number of overtakings performed by different vehicle types within the road section.

For each of the above measures selected for validation, the frequency distribution of the observed and simulated values are compared.

7.3 VEHICLE GROUPS FOR VALIDATION

The various measures need to be analysed for different vehicle types. As the observed traffic compositions have different proportions of vehicles, the number of observations in a particular simulation run vary. It is necessary to have a proper choice of vehicle types, whose performance measures will help to validate the various components of the simulation process. Though each vehicle type is simulated, the overall system performance measures for validation are studied for following vehicle groups:

(i) **Cars/Vans/Jeeps:** These vehicles, including maruti and other newly developed cars, have a sufficient proportion of the total volume and this proportion is increasing on the urban roads. These vehicles have the highest value of free speeds and better acceleration performance capabilities.

(ii) **Motorised Three Wheelers (Tempo/Auto Rickshaw):** On urban roads in India these vehicles form the most prominent mode of public transport and their proportion is even higher that of cars on certain arterials.

(iii) **All Heavy Motor Vehicles (HMV) and Light Commercial Vehicles (LCV):** These are wide body vehicles with low proportion in the traffic mix. These are aggregated to form one group due to wide body.

(iv) **Motorised Two Wheelers:** All types of motorised two wheelers - scooters, motorbikes etc.

(v) **Bicycle:** These are very narrow vehicles, but have the highest proportion in the traffic mix for most of the Indian cities.

(vi) **Cycle Rickshaw:** These vehicles are wider than bicycles and are present in significant proportion.

7.4 ESTIMATION OF PERFORMANCE MEASURES

Model simulates the flow of vehicles on a road as per the traffic input data, and records each event executed during run in chronological order in an "event file". The event file is analysed through the various result processing programs to bring out the performance measures for each of the vehicle. Some performance measures are aggregated over the entire stretch and some are studied at specific points on the road. The following performance measures, are estimated both for the simulated and observed traffic.

7.4.1 Journey Speed Distribution of Different Vehicle Groups

This is the most important measure as journey speed of a vehicle is governed by the free speed, power mass ratio, road geometry, flow level and the various traffic interactions during flow. Journey speed is also accurately observed from video recorded data. In this study, comparison of the observed and simulated traffic for different vehicle groups is made through

- Mean journey speed,
- Standard deviation of journey speeds, and
- Frequency distribution of journey speeds.

Difference between the observed and simulated values of mean and standard deviation show the overall comparison of the group, whereas the nature of frequency distribution tests the dispersions.

7.4.2 Time Headway at Exit for Different Vehicle Groups

Mixed traffic has wide variations in width of vehicle and these do not form any specific lane discipline. Time headways are normally estimated with respect to consecutive vehicles in the same lane. The estimation of this time headways is not appropriate for the heterogeneous mix, as number of vehicles may be moving parallel depending upon the vehicle type. The estimated time headways for the total traffic does not really represent the space between consecutive vehicles.

To have an appropriate measures for time headways in the heterogeneous traffic mix, these are recorded separately for each vehicle group. The headway of a vehicle represents its headway with respect to vehicle ahead of the same group. This in a way could be called as "inter-vehicle group time headways". Though this measure is not used to represent any traffic

system, but comparison of inter-vehicle group headways at exit between the simulated and observed traffic gives a fair idea of the vehicle passing pattern at exit. Agreement between the observed and simulated headways implies that the simulation model is satisfactory.

7.4.3 Traffic Density Distribution

Concentration is normally expressed in terms of number of vehicles per km per lane. For the heterogeneous traffic mix, where the vehicle have wide variations in dimensions and other characteristics, and there is no specific lane discipline, the total density of the road stretch is not a proper measure to test the validity of simulation results. A better approach that has been adopted is with reference to the proportion of road space occupied by the vehicles. It is the total road area occupied by vehicles at an instant. This area takes care of the wide variation in the dimensions of the vehicles. At every 15 sec interval, the number of vehicles of different groups present in the road stretch are recorded both from observed data and simulation results. Knowing the physical dimensions of a vehicle group, the total road space occupied for each group of vehicles is estimated.

The computations of concentration as shown in Figure 7.1 are as follows:

$$\text{Concentration} = \sum_{k=1}^{n} Conc_k \tag{7.1}$$

where $Conc_k$ = concentration of kth vehicle type
n = number of type of vehicles in the traffic mix

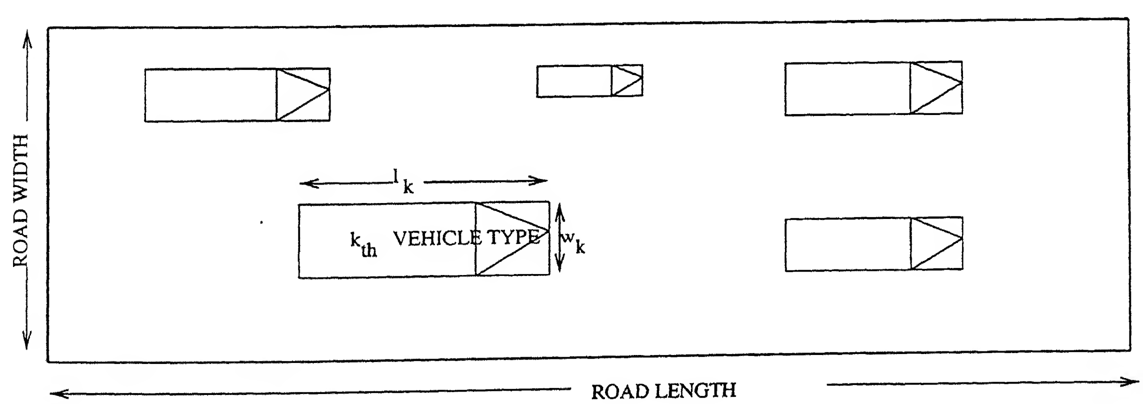


Figure 7.1: Road Occupancy in Terms of Area Occupied by the Vehicles

The computations of the road occupancy as shown in Figure 7.1 are as follows:

$$RS_{traf} = \sum_{k=1}^{n} Conc_k(w_k * l_k) \tag{7.2}$$

where RS_{traf} = road space occupied by traffic
w_k = width of kth vehicle type
l_k = length of kth vehicle type
n = number of type of vehicles in the traffic mix

$$PRS_{traf} = \sum_{k=1}^{n} \frac{Conc_k(w_k * l_k)}{R_l R_w} \tag{7.3}$$

where PRS_{traf} = proportion of road space occupied by traffic
R_l = road length
R_w = road width

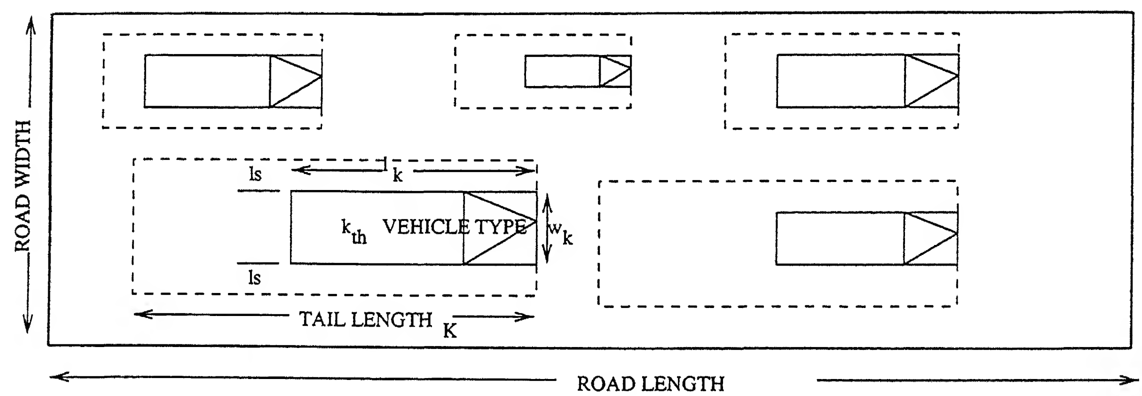


Figure 7.2: Road Occupancy in Terms of Influence Area

Concept of proportion of road space influenced by traffic is adopted for analysing sensitivity experiments. The computations of influence area, as shown in Figure 7.2, are as follows:

$$IA_k = (w_k + 2ls_k) * TL_k \tag{7.4}$$

where IA_k = average influence area of kth vehicle type
ls_k = average lateral space required by kth vehicle type on each side
TL_k = tail length of kth vehicle type

$$TIA = \sum_{k=1}^{n} (IA_k)(Conc_k) \tag{7.5}$$

from one used for calibration. This helps to test the capability of model under different conditions.

Traffic input data for the simulation run is extracted from the observed traffic flow data. This includes identification number, vehicle type, entry time, lateral position at entry, entry speed, and exit time. Input data related to free speed and power mass ratio of the vehicle input is generated as per the calibrated distribution.

7.5.1 Traffic Characteristics

Simulation run is carried out for hourly volume of 2332 vph which is observed during the peak hour of a day. The observed volumes during 15 minute intervals are 554, 557, 601 and 603 giving peak hour factor of (PHF) 0.967. This value of peak hour factor indicates that there is not significant variation of traffic flow within the hour.

Table 7.1: Traffic Volume and Composition for Simulation Run

Time Interval(Minutes)		Volume
0.0-15.0		554
15.0-30.0		574
30.0-45.0		601
45.0-60.0		603
Total (0.0-60.0 minutes)		2332
Vehicle Type	Volume	Proportion Percentage
Car/Van/Jeep	62	2.65
Tempo/Auto Rickshaw	350	15.00
BUS/LCV	29	1.24
Motorised Two Wheeler	334	14.32
Push Cart/ADV	11	0.47
Bicycle	1224	52.48
Cycle Rickshaw	322	13.80
All Non-motorised Vehicles	1557	66.77
All Motorised Vehicles	775	33.23

The composition of different vehicle types as presented in Table 7.1 indicates that traffic mix is highly heterogeneous. Proportion of non-motorised vehicles (66.77 percent) is much higher than that of motorised vehicles (33.23 percent). Amongst the non-motorised vehicles, the most dominating proportion is of bicycles, being about half of the total volume. Cycle

rickshaws are about 13.8 percent of the total flow. Amongst the motorised vehicles, three wheelers (tempos/auto rickshaws) and two wheelers have high proportions. The proportion of tempo is high as it is a major mode for public transport in Kanpur city. The proportion of car is only 2.65 percent with an hourly volume of 62 vph.

7.5.2 Entry Speed

The observed entry speeds are input to the traffic generation submodel. While generating the free speed of vehicle, the observed entry speed is also taken into consideration. Mean and standard deviation of entry speed for different vehicle types is given in Table 7.2. The cumulative frequency distribution of entry speed are presented in Figures 7.3 to 7.4 for some vehicle types. Figures indicate that there is significant dispersion of entry speeds.

Table 7.2: Entry Speed and Lateral Position for Different Vehicle Groups

Vehicle Type	Entry Speed		Lateral Position at Entry	
	Mean (m/sec.)	Standard Deviation (m/sec.)	Mean (m)	Standard Deviation (m)
Car/Van/Jeep	6.33	2.08	5.92	0.69
Tempo/Auto Rickshaw	5.16	1.57	5.13	1.28
LCV/BUS	5.44	1.53	5.44	0.80
Motorised Two Wheeler	6.56	2.21	5.47	1.00
Push Cart/ADV	2.18	0.37	3.51	0.81
Bicycle	4.09	0.79	3.91	0.99
Cycle Rickshaw	3.37	0.78	3.93	1.08
All Non-motorised Vehicles	3.93	0.85	-	-
All Motorised Vehicles	5.87	2.02	-	-
All Vehicles	4.58	1.63	-	-

7.5.3 Lateral Position at Entry

The observed lateral position of the vehicles at entry is also an input to the simulation model. Mean and standard deviation of the observed entry lateral position for different vehicle groups are presented in Table 7.2. This lateral position is represented by the distance of the front right corner of the vehicle from the left side of roadway. This lateral position thus includes

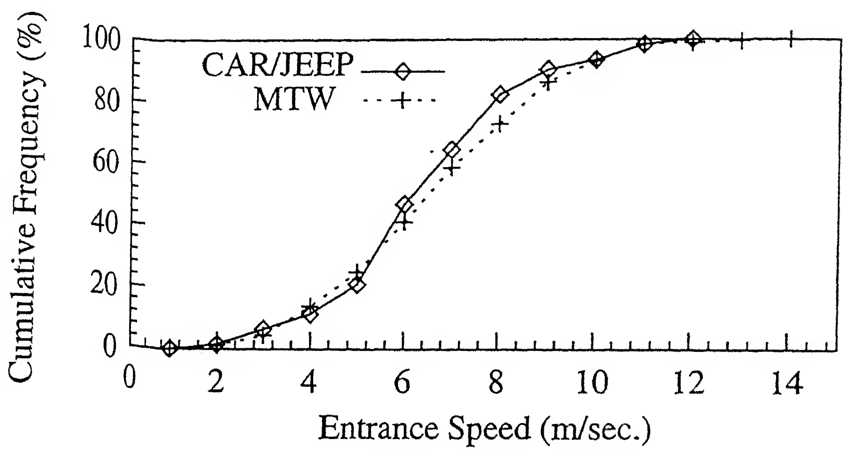


Figure 7.3: Entry Speed Distributions of Car/Van/Jeep and Motorised Two Wheeler

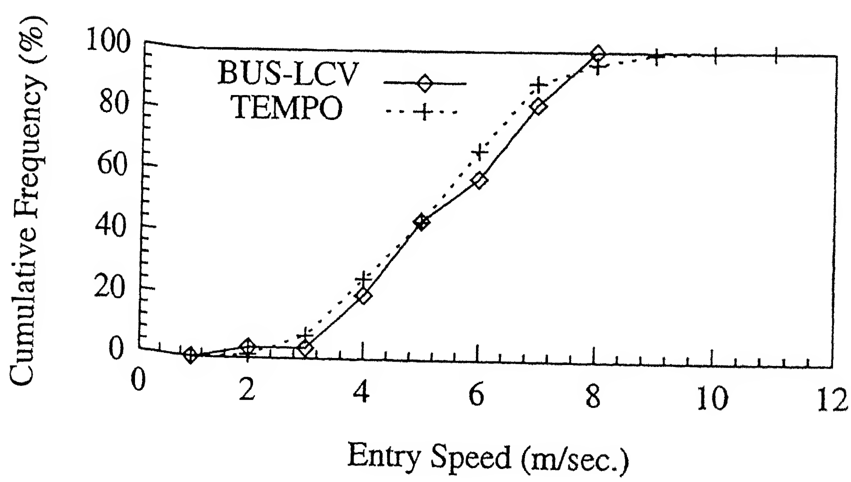


Figure 7.4: Entry Speed Distributions of Bus/LCV and Tempo/Auto Rickshaw

the vehicle width and clear lateral spacing from the road side. It is also observed that the standard deviation is quite high for some vehicle types confirming that there is no specific lane discipline for the vehicles and these move as per the available space along the road width. The cumulative frequency distribution of lateral position for some vehicle types are shown in Figures 7.5 to 7.7.

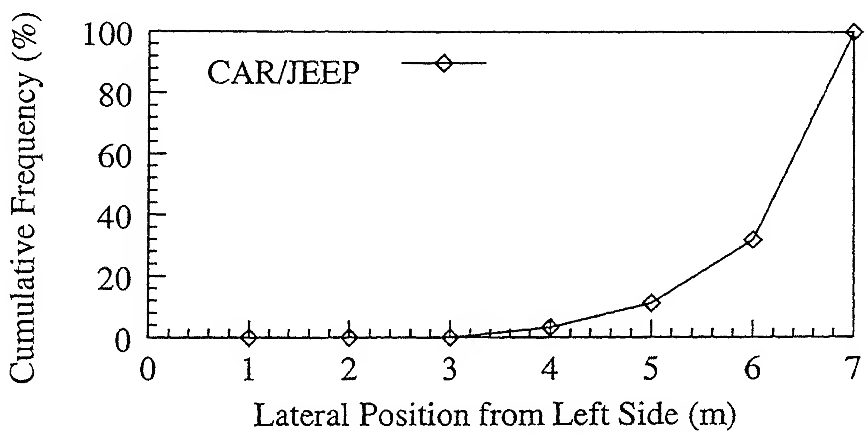


Figure 7.5: Distribution of Lateral Positions for Car/Van/Jeep

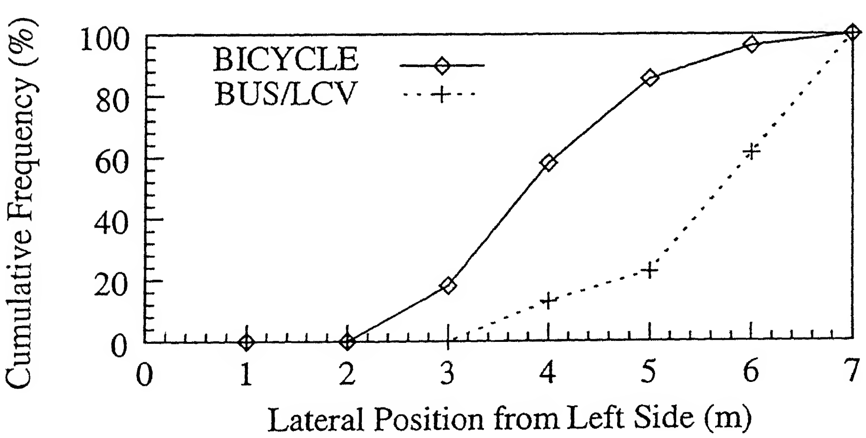


Figure 7.6: Distribution of Lateral Positions for Bicycle and Bus/LCV

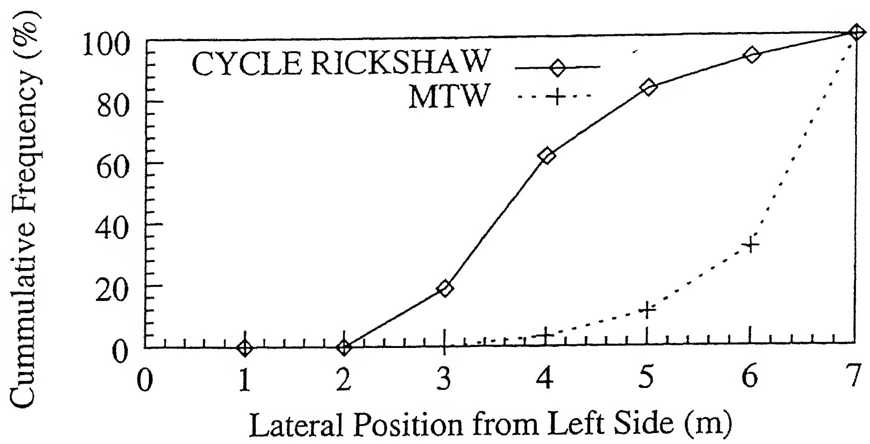


Figure 7.7: Distribution of Lateral Positions for Cycle Rickshaw and Motorised Two Wheeler

7.6 COMPARISON OF SIMULATED AND OBSERVED DATA

Simulation results are analysed to estimate the values of selected performance measures. These estimated values are compared with the observed ones to judge the validity of the simulation model.

7.6.1 Comparison of Journey Speeds

Estimated values of mean and standard deviation of journey speeds, both for observed and simulated traffic, are presented in Table 7.3 for different vehicle groups. The sample size of each vehicle group is also given in the Table 7.3. Bar charts representing the mean and standard deviation of journey speeds are also shown in Figures 7.8 to 7.9. Results indicate that simulated and observed journey speeds are very close, the difference being within about $\pm$ 0.4 m/sec (about 1.5 kmph). Only in one case of car (car/van/jeep), the difference is slightly higher. The standard deviations of observed and simulated journey speeds are very close, being within $\pm$ 0.3 m/sec (1 kmph).

The cumulative frequency distributions of observed and simulated journey speeds are presented in Figures 7.10 to 7.14 for some vehicle groups. The nature of these distributions are quite identical for all cases. The marginal differences in some cases are primarily at very low or very high speeds. Figure 7.15 shows the comparison of observed and simulated mean journey speeds for different vehicle groups. Most of the values are quite close to the 45^o line

indicating a closeness of observed and simulated values.

Table 7.3: Comparison of Journey Speeds

Vehicle Group	Sample Size	Observed		Simulated		Difference of Means (m/sec.)
		Mean (m/sec.)	St. Dev. (m/sec.)	Mean (m/sec.)	St. Dev. (m/sec.)	
Car/Van/Jeep	62	7.07	2.36	7.45	2.62	0.38
Tempo	345	5.26	1.33	5.29	1.53	0.03
BUS/LCV	29	5.88	1.32	6.16	1.89	0.28
Motorised Two Wheeler	329	6.52	1.84	6.28	2.12	-0.26
Push Cart/ADV	11	2.18	0.37	2.19	0.31	0.01
Bicycle	1211	4.01	0.75	3.80	0.87	-0.21
Cycle Rickshaw	316	3.39	0.72	3.43	0.67	0.04
All Non-Motorised Vehicles	1538	3.87	0.80	3.72	0.86	-0.15
All Motorised Vehicles	765	5.97	1.77	5.92	2.03	-0.05
All Vehicles	2303	4.57	1.56	4.45	1.71	-0.12

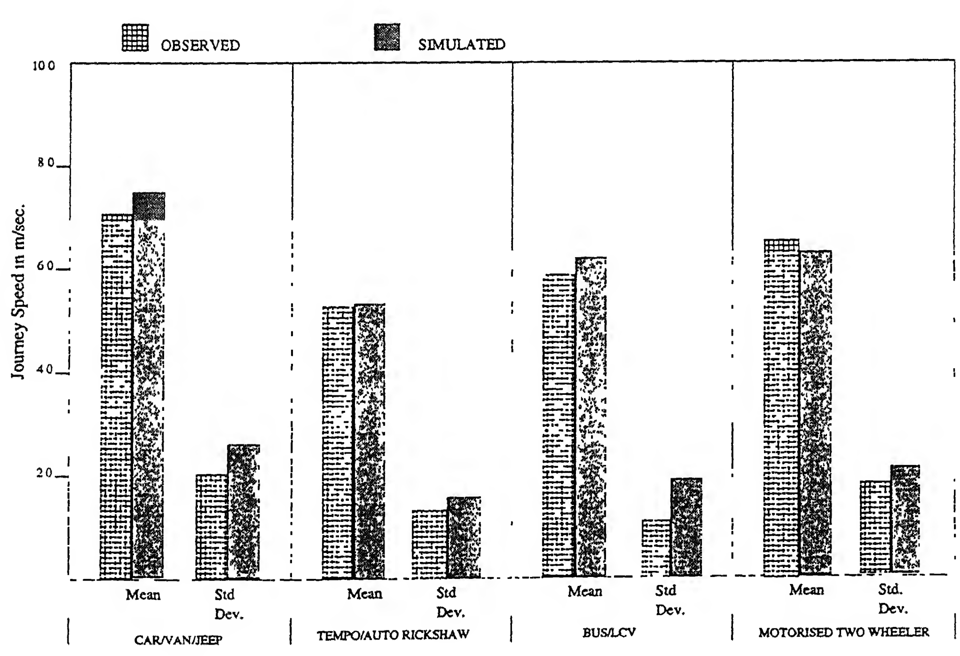


Figure 7.8: Comparison of Journey Speeds

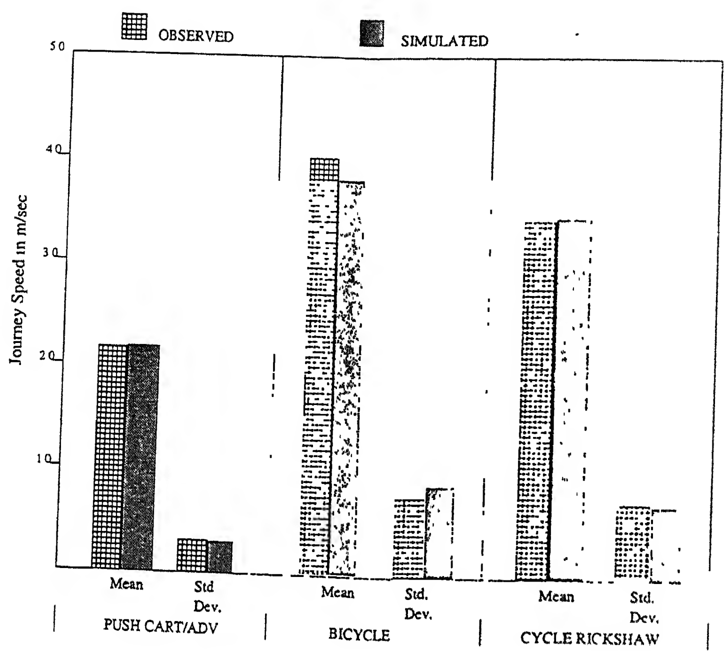


Figure 7.9: Comparison of Journey Speeds

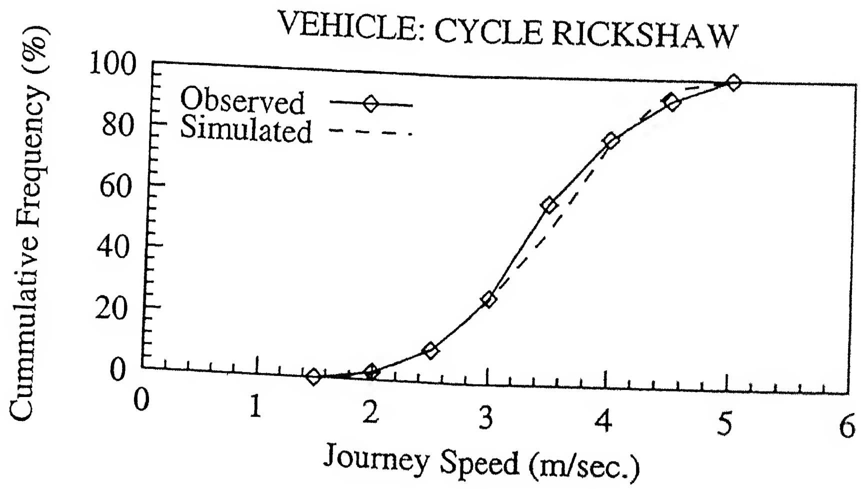


Figure 7.10: Comparison of Observed and Simulated Distributions of Journey Speed for Cycle Rickshaw

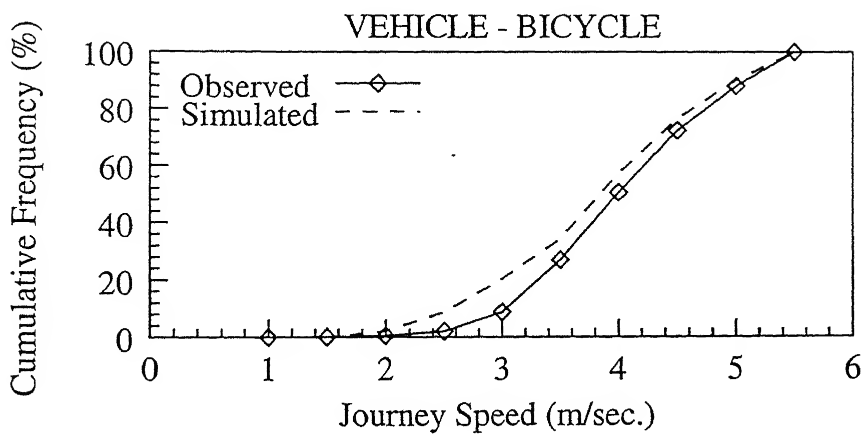


Figure 7.11: Comparison of Observed and Simulated Distributions of Journey Speed for Bicycle

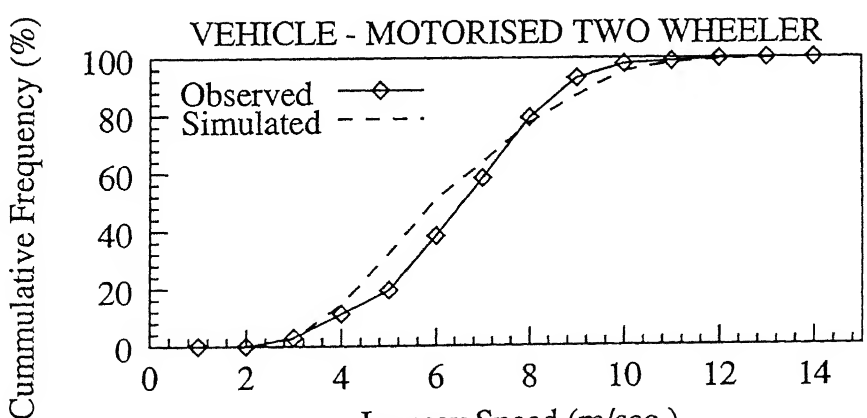


Figure 7.12: Comparison of Observed and Simulated Distributions of Journey Speed for Motorised Two Wheeler

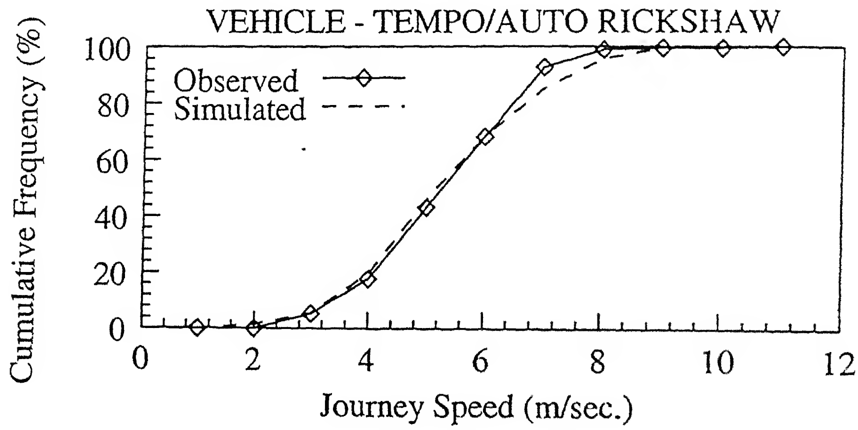


Figure 7.13: Comparison of Observed and Simulated Distributions of Journey Speed for Tempo/Auto Rickshaw

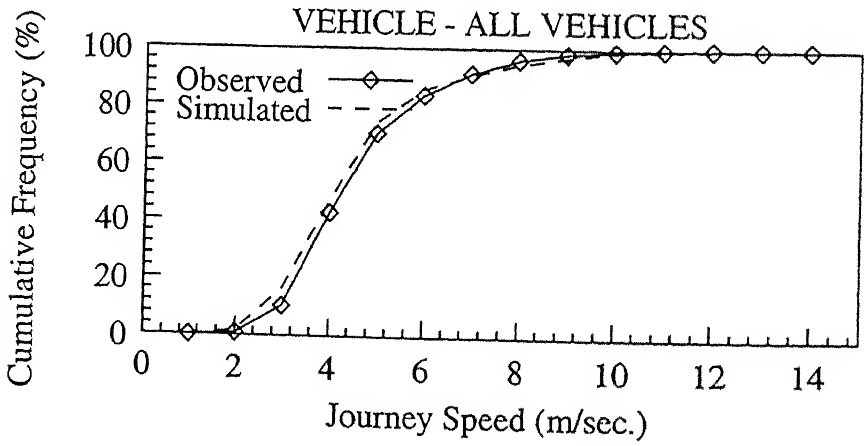


Figure 7.14: Comparison of Observed and Simulated Distributions of Journey Speed for All Vehicles

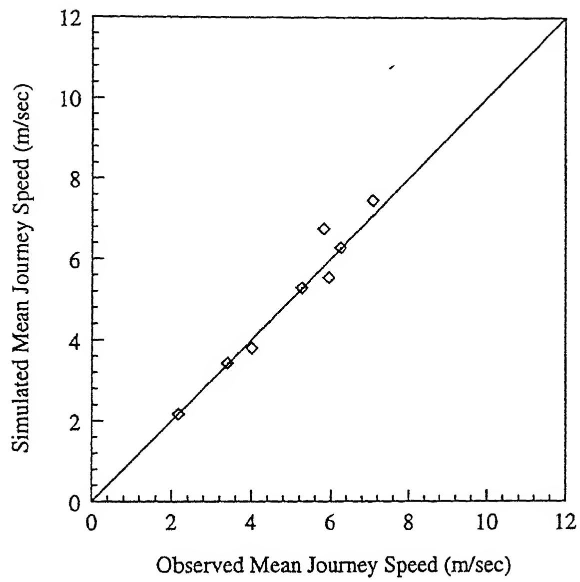


Figure 7.15: Comparison between Observed and Simulated Mean Journey Speeds of Different Vehicle Types

7.6.2 Comparison of Inter Vehicle Group Time Headways at Exit

Estimated values of mean and standard deviation of inter-vehicle group time headways at exit points, are presented in Table 7.4, both for observed and simulated traffic. Bar charts representing the mean and standard deviation of time headways, are also shown in Figures 7.16 to 7.17. The observed and simulated values of mean and standard deviation are quite close for most of the cases. Only for cycle rickshaw, the difference between the standard deviation of observed and simulated traffic is about 1.31 seconds. The cumulative frequency distributions of observed and simulated inter vehicle group exit time headways are presented in Figures 7.18 to 7.20 for different vehicle groups. The nature of these distributions are quite identical for all cases.

7.6.3 Comparison of Traffic Concentration

Density expressed as number of vehicles per unit length is not appropriate for comparison of observed and simulated values for heterogeneous traffic. Because of wide variation in vehicle dimensions and lane occupancy pattern, road occupancy by the vehicles, expressed as proportion of the total road space occupied by the vehicles at an instant, is estimated

Table 7.4: Comparison of Inter Vehicular Group Time Headways

Vehicle Type	Observed Data		Simulated Data		Difference of means (sec.)
	mean (sec.)	s.d. (sec.)	mean (sec.)	s.d. (sec.)	
Car/Van/Jeep	55.78	54.43	55.80	53.90	0.02
Tempo / Auto Rickshaw	10.27	10.55	10.26	10.52	-0.01
Bus/LCV	122.78	93.43	122.46	93.68	-0.32
Motorised Two Wheeler	10.82	15.85	10.83	15.45	-0.01
Push Cart/ ADV	192.12	148.40	192.10	147.68	-0.02
Bicycle	2.95	04.28	2.96	4.43	-0.01
Cycle Rickshaw	11.18	12.70	11.21	14.01	0.03
Non-Motorised Vehicle	2.32	3.11	2.32	3.32	0.0
Motorised Vehicle	4.65	6.10	4.66	5.72	0.01
Combined Traffic	1.55	1.79	1.55	1.83	0.0

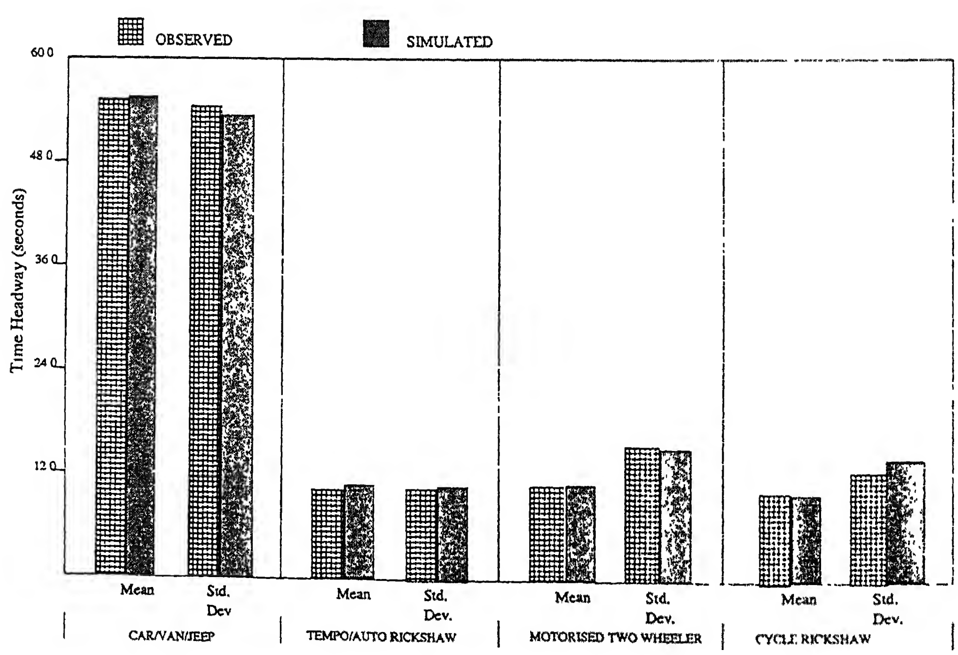


Figure 7.16: Comparison of Inter-Vehicle Group Time Headways at Exit

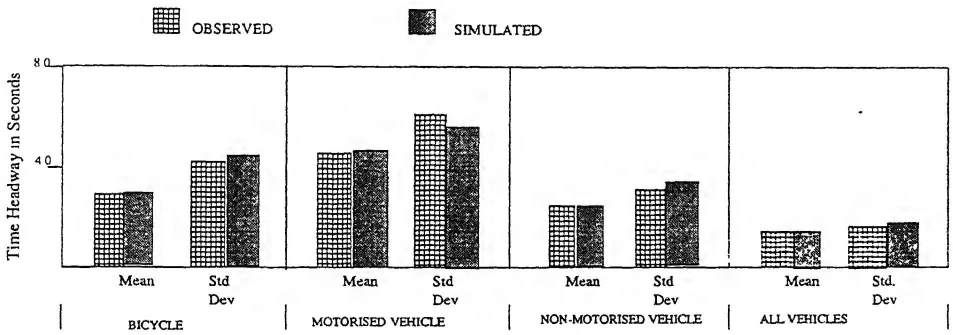


Figure 7.17: Comparison of Inter-Vehicle Group Time Headways at Exit

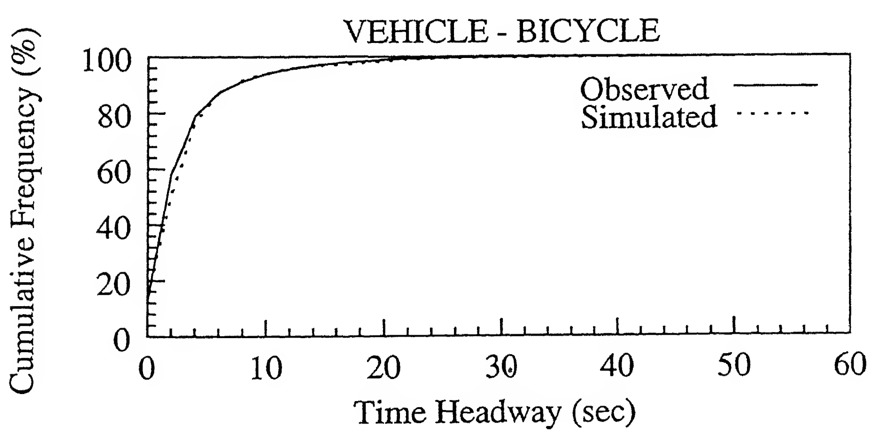


Figure 7.18: Comparison of Observed and Simulated Distributions of Inter Vehicle Group Time Headways for Bicycle

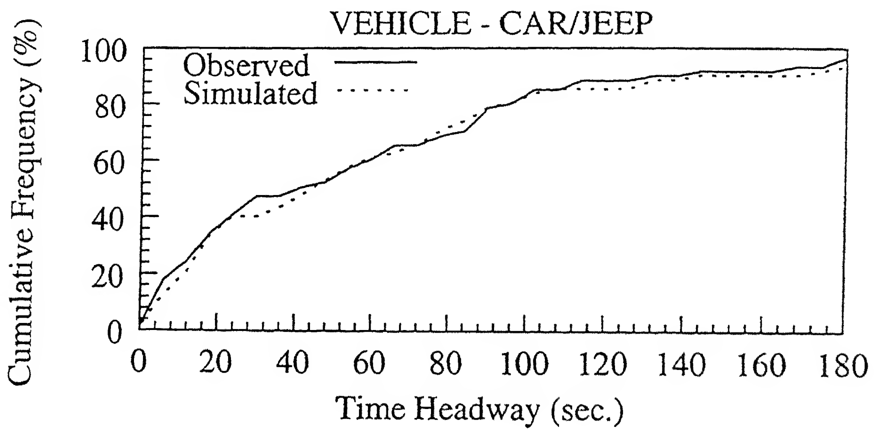


Figure 7.19: Comparison of Observed and Simulated Distributions of Inter Vehicle Group Time Headways for Car/Van/Jeep

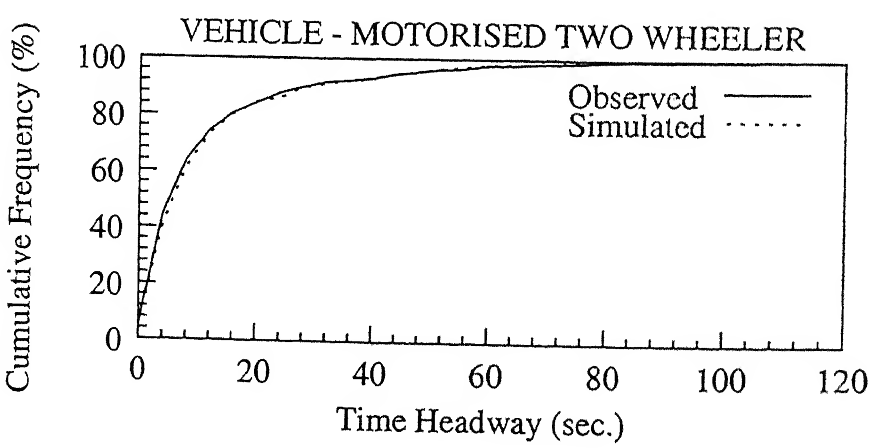


Figure 7.20: Comparison of Observed and Simulated Distributions of Inter Vehicle Group Time Headways for Motorised Two Wheeler

both for simulated and observed data. The measure of road occupancy is definitely superior. The road occupancy is estimated at every 15 second interval.

The variation of road occupancy over time is shown in Figure 7.21 both for simulated and observed data. It is observed that the variation of simulated values over time is generally identical to the observed values. The difference between the two is more only when there are sharp fluctuations. Mean and standard deviation of the road occupancy recorded at every 15 second interval are shown in Figure 7.22 both for observed and simulated values.

The mean road occupancy for the observed data is 4.99 percent (percent of total road area) and 5.23 percent for the simulated values (Table 7.5). This difference is marginal due to wide dispersion of the values. Further these values are being taken only at fixed intervals of 15 seconds. This comparison shows that the model behaviour is identical to observed data with regard to presence of vehicles in road stretch.

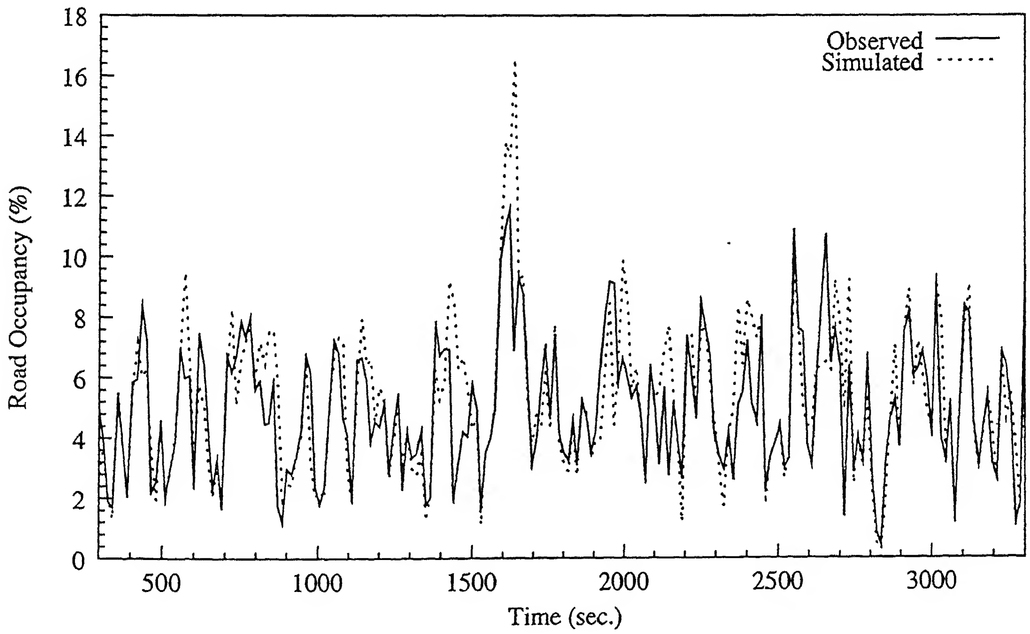


Figure 7.21: Comparison of Observed and Simulated Road Occupancy

7.6.4 Comparison of Overtakings

Simulated values of the number of flying/accelerative overtakings performed by different vehicle groups are presented in Table 7.6. The model records each type of overtaking/passing but it is not possible to determine the types of overtaking from the field data. To compare

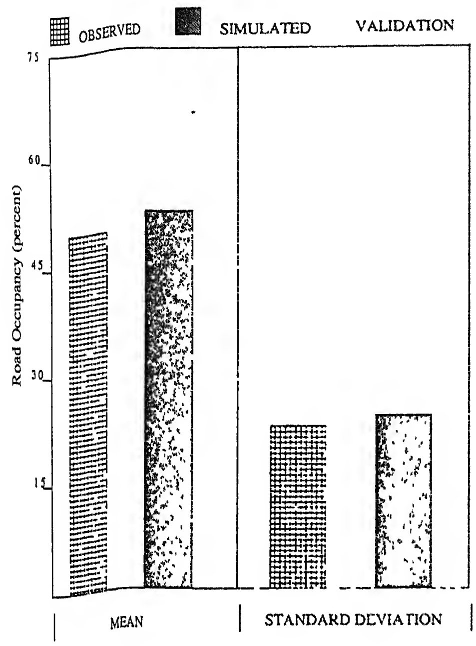


Figure 7.22: Comparison of Observed and Simulated Road Occupancy

Table 7.5: Comparison of Observed and Simulated Road Occupancy

	Road Occupancy in Percent	
	Mean	Standard Deviation
Observed	4.99	2.22
Simulated	5.23	2.38

the number of overtakings for the model and the observed data, an estimate is based on the entry and exit time of the vehicles for both the cases. This estimate may miss some overtaking/passing performed by the vehicles, but can be effectively used for comparison between the simulated and observed values.

For comparison grouping of the vehicles is as follows:

- Car, Van, Jeep, Tempo, and Auto-rickshaw
- Heavy Vehicles (Bus/Truck/Light Commercial Vehicles)
- Motorised Two Wheelers
- All non-motorised vehicles

The observed and simulated values are presented in Table 7.7. Bar charts representing the overtakings of three/four wheeled motorised vehicles, two wheeled motorised vehicles, all motorised vehicles and all non-motorised vehicles by some of the groups are shown in Figure 7.24 to 7.26. The simulated and observed values are quite comparable for most of the cases. This demonstrates the capability of the simulation model to realistically represent the complex heterogeneous traffic flow.

7.6.5 Conclusions

Comparison between the observed and simulated values for different measures demonstrates that the formulation and calibration of the simulation model is acceptable. This validation exercise is of limited nature as model has been tested for only one road stretch. It is suggested that sensitivity of different model parameters is studied and validation exercise is also carried out for different roads of varying width and length.

7.7 SUMMARY

The measures of effectiveness selected for validation are: journey speeds, time headways, traffic density, and number of overtakings performed. For each of the measure selected for validation, the frequency distribution of the observed and simulated values are compared. For comparison of observed and simulated values, different vehicle types are divided into six groups. These groups are cars, motorised three wheelers (Tempo/Auto Rickshaw), heavy motor and light commercial vehicles, motorised two wheelers, bicycles, and cycle rickshaws.

Table 7.6: Overtaking Operations During Simulation Run

Accelerated Overtaking Distribution							
Overtaking Vehicle Group	Overtaken Vehicle Group						
	1 Car/ Van/ Jeep	2 Tempo	(3+4) Bus/ LCV	5 Motorised Two Wheeler	6 Push Cart ADV	7 Bicycle	8 Cycle Rickshaw
1 (Car/Van/Jeep)	1	17	4	11	0	42	6
2 (Tempo)	5	50	4	22	0	44	205
(3+4) (Bus/LCV)	2	0	0	8	0	31	12
5 (Motorised Two Wheeler)	6	28	1	15	0	18	56
6 (Push Cart/ADV)	0	0	1	0	0	3	2
7 (Bicycle)	19	97	2	56	2	849	179
8 (Cycle Rickshaw)	0	14	0	17	1	169	39
Flying Overtaking Distribution							
Overtaking Vehicle Group	Overtaken Vehicle Group						
	1 Car/ Van/ Jeep	2 Tempo	(3+4) Bus/ LCV	5 Motorised Two Wheeler	6 Push Cart ADV	7 Bicycle	8 Cycle Rickshaw
1 (Car/Van/Jeep)	2	10	0	3	0	2	14
2 (Tempo)	5	18	0	9	1	27	88
(3+4) (Bus/LCV)	0	0	0	2	0	2	12
5 (Motorised Two Wheeler)	1	12	0	7	0	3	10
6 (Push Cart/ADV)	0	0	0	0	0	0	0
7 (Bicycle)	4	16	2	11	0	18	76
8 (Cycle Rickshaw)	3	5	0	0	0	7	12
Total Number of Overtakings 2420							

Table 7.7: Comparison of Observed and Simulated Overtaking Distributions

Overtaking Vehicle Group	Overtaken Vehicle Group							
	(1+2) Car/ Van/ Jeep/ Tempo	(3+4) Bus/ LCV	5 Motorised Two Wheeler	(6+8) Push Cart/ ADV/ Cycle Rickshaw	7 Bicy-cle	ALL NMVs	ALL MVs	ALL Vehicles
(1+2) Car/Van/ Jeep/Tempo								
Observed	127	6	70	409	842	1251	203	1454
Simulated	106	6	73	346	910	1206	185	1441
(3+4) Bus/LCV								
Observed	5	1	3	30	53	83	9	92
Simulated	3	0	5	26	64	90	8	98
(5) Motorised Two Wheeler								
Observed	174	3	123	339	739	1078	300	1378
Simulated	151	5	155	295	753	998	316	1359

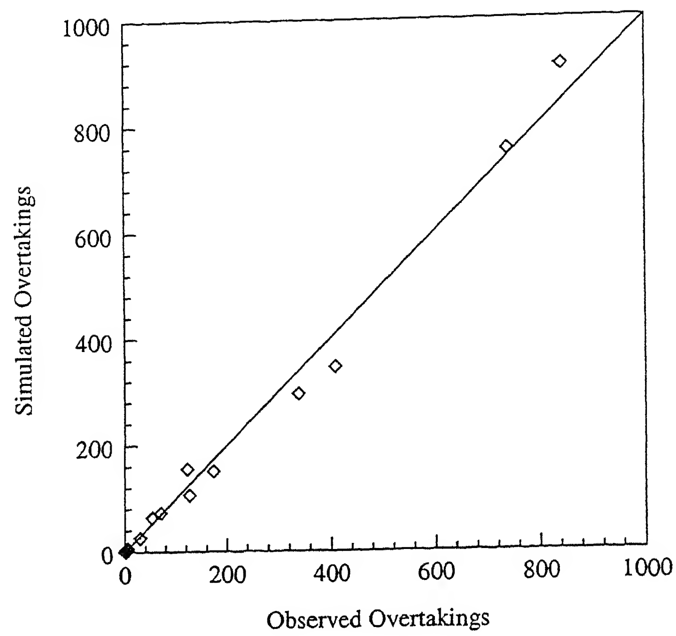


Figure 7.23: Comparison of Observed and Simulated Overtakings for Validation (Combined Traffic)

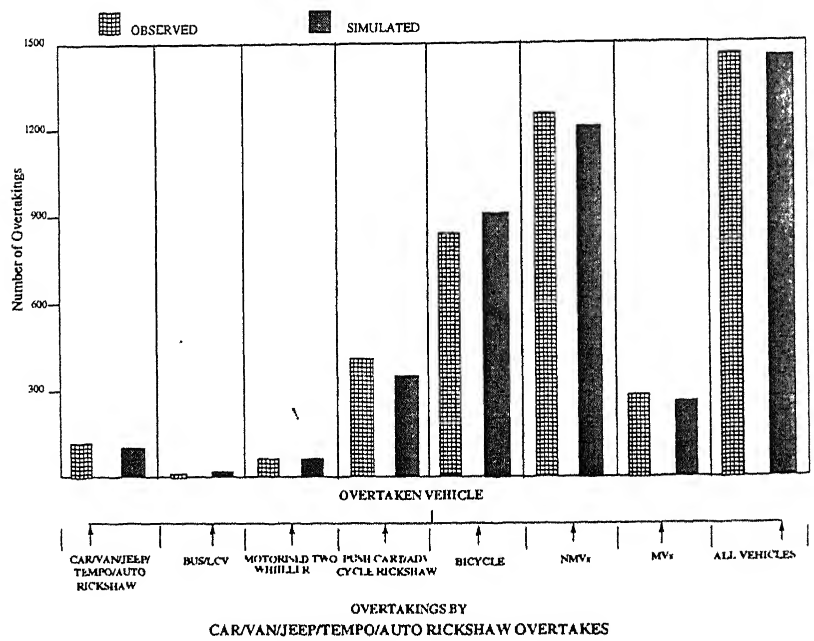


Figure 7.24: Comparison of Overtakings

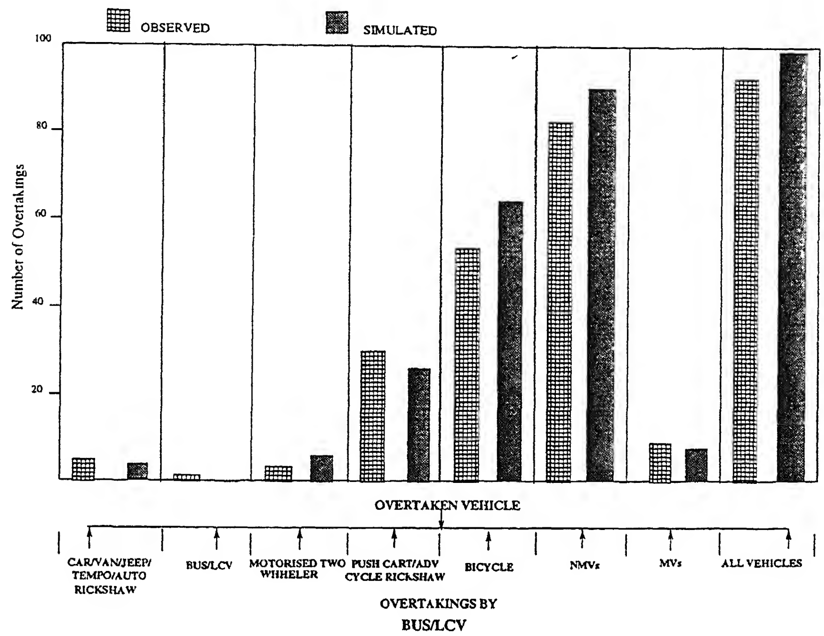


Figure 7.25: Comparison of Overtakings

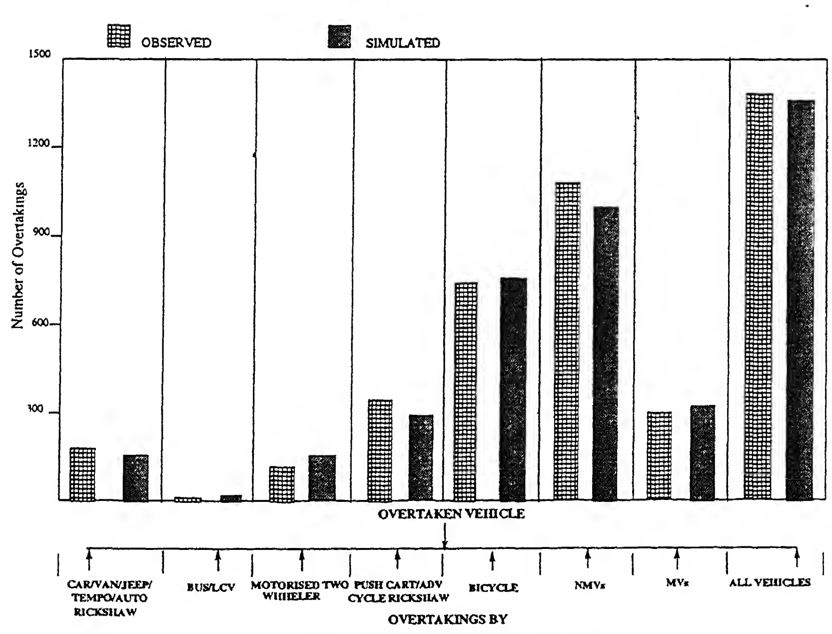


Figure 7.26: Comparison of Overtakings

Concentration is normally expressed in terms of number of vehicles per km per lane. For the heterogeneous traffic mix, the vehicles have wide variation in dimensions and other characteristics, and there is no specific lane discipline. A better approach adopted is with reference to the proportion of road space occupied by the vehicles. Concept of proportion of road space influenced by traffic is also adopted for analysing sensitivity experiments. Comparison of the observed and simulated road space occupancy or influence area is made through:

- Variation of road occupancy over a period, the observations being made at every 15 sec interval.
- Maximum road space or influence area at any instant during the simulation run. This measure shows the effect of platooning.
- Mean and standard deviation of the road occupancy.

Simulation runs are made at flow level different from one used for calibration. This helps to test the capability of model under different conditions. Simulation run is made for an hourly volume of 2332 vph observed during the peak period.

Estimated values of mean and standard deviation indicate that simulated and observed journey speeds are very close. The observed and simulated values of mean and standard deviation of inter-vehicle group time headways at exit are quite close for most of the cases. The variation of road occupancy over time is studied both for simulated and observed data. Variation of simulated values over time is generally identical to the observed values. The simulated and observed number of overtakings are quite comparable for most of the cases. These comparisons demonstrate the capability of the simulation model to realistically represent the complex heterogeneous traffic flow.

Chapter 8

SENSITIVITY ANALYSIS

8.1 INTRODUCTION

After successful calibration and validation, the simulation model can now be applied for experiments under different road, traffic, and other operating conditions such as segregation of motorised and non-motorised vehicles, providing separate bus/car lane. Analysis of the simulation results may be used to estimate the level of service under different operating conditions. Simulation results may also help to identify the deficiencies of an urban road system and to plan for alternative improvements to attain a desired level of service. Sensitivity analysis of some roads and traffic characteristics are attempted in this study.

8.2 DESIGN OF SIMULATION EXPERIMENTS

The study aims to perform sensitivity analysis of various road and traffic characteristics by conducting a series of simulation runs. There are number of parameters related to road and traffic characteristics, which may be of interest for Indian urban roads. Each parameter may also have number of levels commonly encountered. A full factorial design of the different parameters and their levels may result into very large number of runs and it may be highly time consuming. However, to test the rationality of the model logics and capability of the developed model system a series of simulation runs are planned.

8.2.1 Road Characteristics

Sensitivity analysis of the following road characteristics may be of interest:

- Road width
- Horizontal and verticle alignment

- Road usage
  - Restricting the use of road space for non-motorised vehicles
  - Unrestricted use of road space by non-motorised vehicles

Initially a two lane (7m) wide level tangent road section (Road - I) is selected for simulation runs. As this is the road for which data was collected for calibration and validation of the simulation model, this is the benchmark road on which simulation experiments are planned for different traffic characteristics. To test the sensitivity of road width, two more roads, three lane (10 m) wide and four lane (14 m) wide, are considered for simulation runs. The benchmark road and other two roads have unrestricted use by all non-motorised vehicles. To study the effect of restricting the road usage (segregation) of non-motorised vehicles, simulation experiments are planned only on 7 metre wide road where the non-motorised vehicle are restricted only to one lane (3.5 m width) adjacent to the road kerb. This lane could, however, be used by motorised vehicles. The lane adjacent to the median is only utilised by motorised vehicles.

8.2.2 Length of Road Sections

For unbiased estimation of traffic flow characteristics, a certain minimum road length should be simulated. This minimum road length depends upon the road geometrics and traffic flow. A longer simulated road length is definitely better for estimation of traffic flow parameters. The roads have intersections at closed space in urban areas. Road stretch of 500 m length along with warming up zone of 300 m length is choosen in this study for simulation experiments (Figure 8.1). This length is appropriate to study the traffic interactions and to estimate traffic flow parameters.

The simulation model requires the following traffic input for each vehicle at entry to the road section.

- Vehicle type and its dimensions
- Entry coordinates
- Free speed
- Power mass ratio
- Entry time
- Entry speed

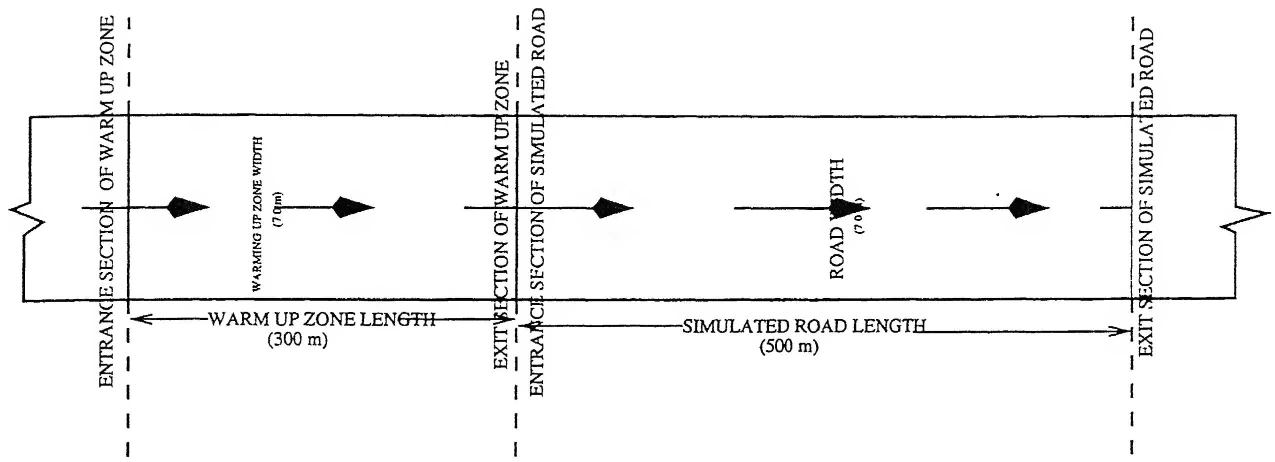


Figure 8.1: Simulated Road Stretch along with Warming Up Zone

- Lateral position at entry

First five parameters are generated based on traffic flow and composition. However, it is not possible to estimate the entry speed and lateral position at entry. For the simulation experiments conducted for calibration and validation, the observed data for entry speed and lateral position was available. But for experiments of sensitivity analysis, these inputs need to be generated. The entry speed and lateral position of the vehicle depends upon the flow level and its interaction with other vehicles in close vicinity. Due to these factors a simple generation is not appropriate. To have a realistic generation of entry speed and lateral position, an additional warm up road section is included before the actual road stretch is to be simulated. The vehicles are generated and moved in the warm up section as per the simulation model. The vehicle characteristics at the end of warm up section are given as input for the actual road stretch and the simulation is continued. In this manner entry speed and lateral position will be quite realistic as it is output of the simulation flow process.

8.2.3 Traffic Characteristics

Simulation experiments are planned to test the sensitivity of only following two characteristics:

- Traffic composition

- Traffic flow level

Traffic Composition

Composition of different types of vehicles in traffic mix significantly affects the flow process as there are wide variations in dimensions, free speeds, acceleration/ deceleration capability of different vehicle types. Based on the observed traffic composition in Kanpur a benchmark traffic composition (Level I) is selected for simulation runs for all the four identified roads. This benchmark composition has 35 percent of motorised vehicles and 65 percent of non-motorised vehicles. The proportion of individual vehicle types are given in Table 8.1. To study the effect of other traffic compositions, two more compositions (Level II and III) are specified. Level II composition has equal share of motorised and non-motorised vehicles. The proportion of individual vehicle types are accordingly selected. Selected level III composition has domination of motorised vehicles (65 percent), while non-motorised vehicles are 35 percent. The proportion of each vehicle type is accordingly identified:

Table 8.1: Traffic Composition for Simulation Runs

Vehicle Type	Proportion in percent		
	Level-I	Level-II	Level-III
Cars/Vans/Jeeps	5.0	10.0	15.0
Buses/Trucks/LCVs	2.5	5.0	5.0
Tempos/Auto Rickshaws	12.5	15.0	20.0
Motorised 2-Wheelers	15.0	20.0	25.0
Non-Motorised 2-Wheelers	50.0	35.0	25.0
Non-Motorised 3-Wheelers	14.5	15.0	10.0
Non-Motorised, other Traffic Entities	0.5	0.0	0.0
Motorised Vehicles	35.0	50.0	65.0
Non-Motorised Vehicles	65.0	50.0	35.0

Composition of traffic mix for all the three levels are presented in Table 8.1. Level II and III compositions study the effect of high proportion of motorised vehicles. Simulation experiments for these composition are made only on the benchmark road (Road - I).

Traffic Flow Level

Simulation runs are planned at increasing flow levels till flow approaches unstable state. For each road section simulation runs are made at unidirectional flow levels of (600, 900, 1200, 1800, 2400, 3000, 3600, 4200, and 4800 vph). The highest flow level that produces unstable state depends upon the road characteristics and traffic composition. Six series of simulation runs are presented in Table 8.2. Each series has 8-10 flow levels and this results in about sixty simulation runs.

Free Speed Distribution

Free speed distribution is one of the most important characteristics affecting the operating speed of vehicles. The estimated value of parameters for normal distribution as given in Chapter 5, are used for traffic generation.

Table 8.2: Experimental Design of Simulation Runs

Series No.	Road Width (metre)	Traffic Composition	NMV Road Usage	Simulated Flow Levels (vph)
1	7.0	Level I	Unrestricted	600, 900, 1200, 1800, 2400 3000, 3600, 4200, 4800
2	7.0	Level I	Restricted to 3.50 metre	600, 900, 1200, 1800, 2400 3000, 3600, 4200, 4800
3	7.0	Level II	Unrestricted	600, 900, 1200, 1800, 2400 3000, 3600, 4200, 4800
4	7.0	Level III	Unrestricted	600, 900, 1200, 1800, 2400 3000, 3600, 4200, 4800
5	10.0	Level I	Unrestricted	600, 900, 1200, 180, 2400 3000, 3600, 4200, 4800, 5400, 6000, 6600
6	14.0	Level I	Unrestricted	600, 900, 1200, 1800, 2400 3000, 3600, 4200, 4800, 5400, 6000, 6600, 7200, 7800, 8400

8.2.4 Strategies for Simulation Runs

Length of Simulation Experiments

Each simulation run should be long enough to simulate sufficiently large number of vehicles. The objective of simulation analysis is to compare the outputs under different flow rates, traffic compositions and road usage by non-motorised vehicles. Therefore, it is planned to simulate the traffic of 1600 vehicles which results in adequate sample size for analysis. Duration of simulation runs varies depending upon flow rate to be simulated.

Starting Conditions

When simulation is started with an empty road system, first few vehicles move under free flow condition, without any interactions with other vehicles present in the road system (transient state). To eliminate the effect of this transient state, it was decided to ignore the statistics of first one hundred vehicles moving over the road stretch. The remaining sample size of 1500 vehicles is sufficiently large enough to draw conclusions and inferences.

8.3 STRATEGY FOR ANALYSIS OF SIMULATION RUNS

The simulation results for different experiments are analysed to

- Study the effect of various parameters defining the level of service under different flow levels for each simulated road. This analysis can also be used to establish the relationships to estimate the performance parameters.
- Comparison of the flow performance measures for different roads.

Performance measures considered for analysis at each simulation run are:

- Journey speed distribution of different vehicle types
- Mean acceleration noise for different vehicle types. Acceleration noise of a vehicle is defined as the standard deviation of the variation about the mean acceleration.
- Road Concentration: This is studied in three different ways:
  - Number of vehicles in the road section.
  - Road occupancy expressed as total vehicle area in relation to the road area.
  - Vehicle influence area expressed as proportion of road area.

- Overtaking/passing maneuvers executed by different combinations of overtaking and overtaken vehicle types.

Performance measures like journey speed, acceleration noise, overtakings can be estimated for all the simulated vehicles. For concentration measures observations could be made at any time instant. For an unstable/congested flow system, the performance measures may change along time when platoon formation takes place. To judge the unstable state of the system, the performance measures are also studied along time at interval of 100 seconds. This analysis may help to estimate the road capacity.

8.4 ANALYSIS OF RESULTS FOR BENCH MARK ROAD (ROAD - I) AND TRAFFIC COMPOSITION OF LEVEL-I

The benchmark road (Road - I) is 7m wide with unrestricted road usage for non-motorised vehicles. This is simulated for traffic composition of level I which has 35 percent of motorised and 65 percent of non-motorised vehicles. Starting with a flow level of 600 vph simulation runs are made at flow levels of 900, 1200, 1800, 2400, 3000, 3600, 4200, and 4800 vph. A total of 1600 vehicles are simulated for each flow level. The statistics of first 100 vehicles are ignored as they may be moving in a transient state. The estimation of performance measures are done for 1500 vehicles in each flow level.

To estimate the flow level which results in unstable flow condition resulting into platoon formation, the simulation results for high flow levels are studied along time at 100 second intervals. Figure 8.2 shows the variation of mean journey speeds of cars along time at flow level of 3000, 3600, 4200 and 4800 vph. It is observed that for flow levels of 3000 and 3600 vph there is no variation of journey speed along time except for minor random fluctuations. For flow levels of 4200 vph and 4800 vph, the mean journey speed reduces with time. This indicates that the flow may be in a unstable state.

The variation of road occupancy along time is also shown in Figures 8.3-8.4 for high flow levels of 3000, 3600, 4200 and 4800 vph. Road occupancy is observed at every 100 sec. interval till entry of last vehicle. As the number of vehicles being simulated is same for simulation experiment, the entry time of the last vehicle depends upon the flow level. These results show that at highest flow level of 4800 vph, the road occupancy is increasing with time while it has only minor random fluctuations at flow level of 3000 vph.

The above results have demonstrated that the simulated traffic flow is in an unstable state at higher flow levels. For a stable flow condition, the number of vehicles on the road

stretch will have only random variations along time. Figures 8.5-8.6 show separately the cumulative number of vehicles entering and leaving at different times. The difference between these two curves represent the number of vehicles present on the road section (density). For the flow level of 3000 vph (Figure 8.5), the two curves are almost parallel and the system is in a stable state. The cumulative number of vehicles entering and leaving at different times are shown in Figure 8.6 for three flow levels of 3600, 4200 and 4800 vph. It is observed that number of vehicles leaving the road stretch at different times are almost identical for flow levels of 4200 and 4800 vph. This demonstrates that the flow is in an unstable state with concentration increasing over time. Above study of simulation results along time clearly indicates that the traffic flow starts approaching the unstable state at flow level of 4200 vph. At flow levels of 4800 vph the system is in an unstable state. The capacity of this road could be around 4200 vph.

Mean and standard deviation of journey speeds for different vehicle types are presented in Table 8.3 for different traffic flow levels. Figure 8.7 shows the journey speed-flow relationships for different vehicle types. Journey speeds reduce with flow and the level of speed reduction depends upon the vehicle type. Vehicles of high free speed, i.e., cars and motorised two wheelers have high speed reductions even at low flow levels as these vehicles encounter more interactions in the traffic stream. Journey speed of non-motorised vehicles have very minor variations with flow level. These slow moving vehicles significantly affect the speed of faster vehicles, but, they themselves keep moving at close to the free speed. At low flow levels, the journey speeds of motorised vehicles (i.e., car, tempo) are significantly higher than those of non-motorised vehicle's. But as flow increases, this difference reduces and at very high flow levels the speeds of motorised and non-motorised vehicles are very close indicating that flow is moving in platoons and the speed is being dictated by the non-motorised vehicles.

The acceleration noise for the simulated vehicles at different flow levels is presented in Table 8.4 for different vehicle types. The variation of acceleration noise with flow level is also shown in Figure 8.8. Acceleration noise is the standard deviation of the mean acceleration. For faster vehicles like cars, the acceleration noise is very high as these vehicles interact with other vehicles and perform lot of acceleration/deceleration during the movement. The acceleration noise increases with flow level for all vehicle types indicating that model is realistically performing the interactions at low and high flow levels.

Road concentration is observed at every 100 second interval. The mean and maximum concentration for different flow levels is presented in Table 8.5 and is also shown in Figure 8.9. Results show that both concentration increases almost linearly with flow level. As vehicles

in the simulated traffic mix have wide variations in the dimensions, the concentration can be realistically expressed in terms of vehicle road occupancy and vehicle influence area. The mean, standard deviation and the maximum observed road occupancy and vehicle influence area are presented in Table 8.5 for different flow levels. The variation of vehicle road occupancy and influence area with flow level is also shown in Figure 8.10 and Figure 8.11. It is observed that road occupancy increases at a certain rate upto 1800 vph and beyond this flow, the rate of increase is higher. The analysis of above results have demonstrated that speed and concentration are affected by flow level. The relations between speed and concentration are shown in Figure 8.12 for two cases, one for cars and the other for all vehicles. It is observed that mean journey speed of all vehicles varies almost linearly with concentration. However, for cars the speed variation is very high even at low concentration levels. It is observed that at flow level of 4200 vph, the mean concentration of the 500 m long road stretch is 163 vehicles. As this is a two lane road, the concentration per km per lane is also 163.

The overtakings/passings performed in the simulation model for different vehicle combinations are presented in Table 8.6 for different flow levels. These operations are with respect to 1500 vehicles for which statistics are studied. The variations of overtakings with flow are also shown in Figure 8.13 for some combinations. These overtakings/passings also include those operations where a vehicle may pass in the adjoining lane without any interaction. Results indicate that upto 3000 vph the overtakings performed on wide motorised vehicles (car,tempo, bus) both by wide and narrow motorised vehicles are almost same. These overtakings are generally performed on tempos, which has low free speeds. Beyond flow levels of 3000 vph, narrow motorised vehicles perform more overtakings than wide motorised vehicles. This means that scooters perform more overtakings on tempos than cars/jeeps. At these high flow levels, the narrow motorised vehicles are able to perform more manoeuvering than wide vehicles. It is also observed that overtakings of non-motorised vehicles both by wide and narrow motorised vehicles increase with flow level upto 3000 vph. Beyond this level, number of overtakings show a little downward trend. This happens because of close headways, the overtakings/passings are difficult to perform.

8.4.1 Level Of Service

The level of service (LOS) is a composite of several operating characteristics that are supposed to measure the quality of service as perceived by the user at different flow levels. For example one could consider travel speed, congestion level, freedom to maneuver etc. to be factors contributing to LOS. Based on the simulation results of benchmark road (Road - I)

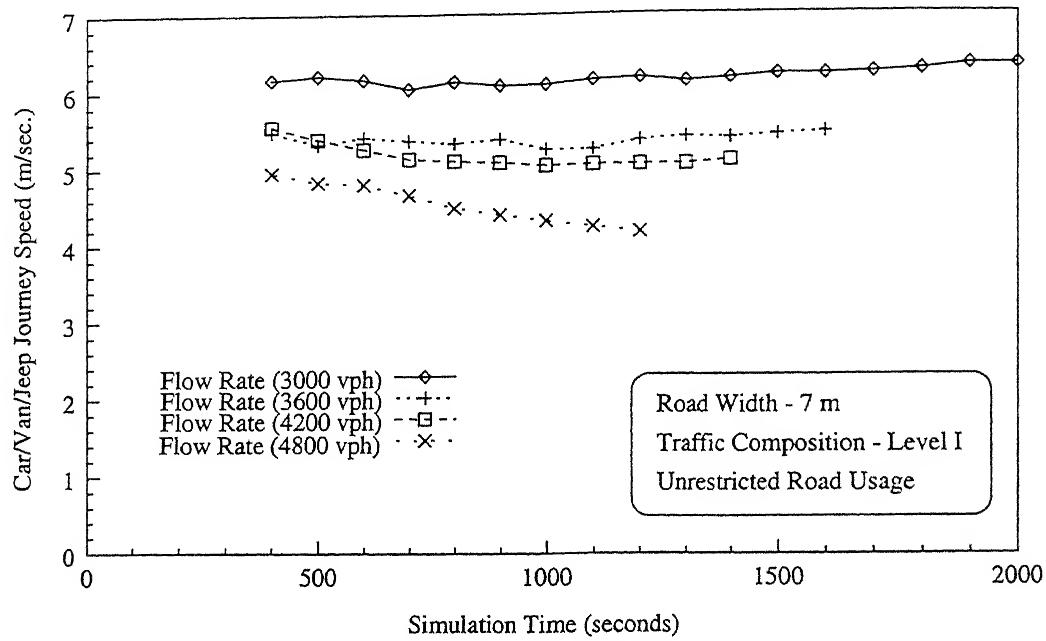


Figure 8.2: Mean Journey Speed - Time Relationships

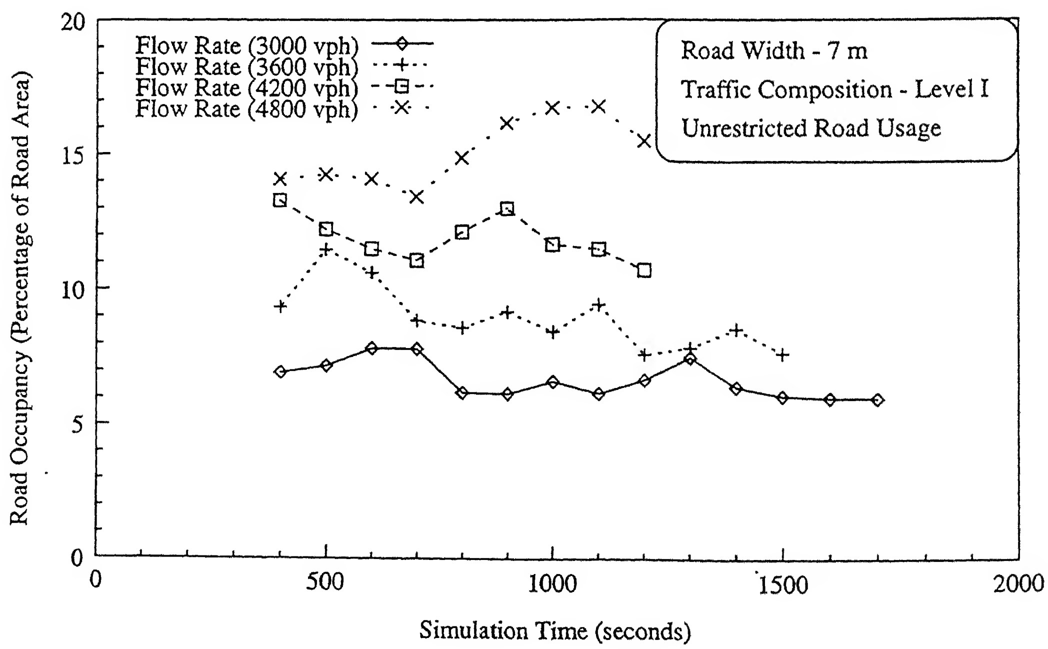


Figure 8.3: Road Occupancy - Time Relationships

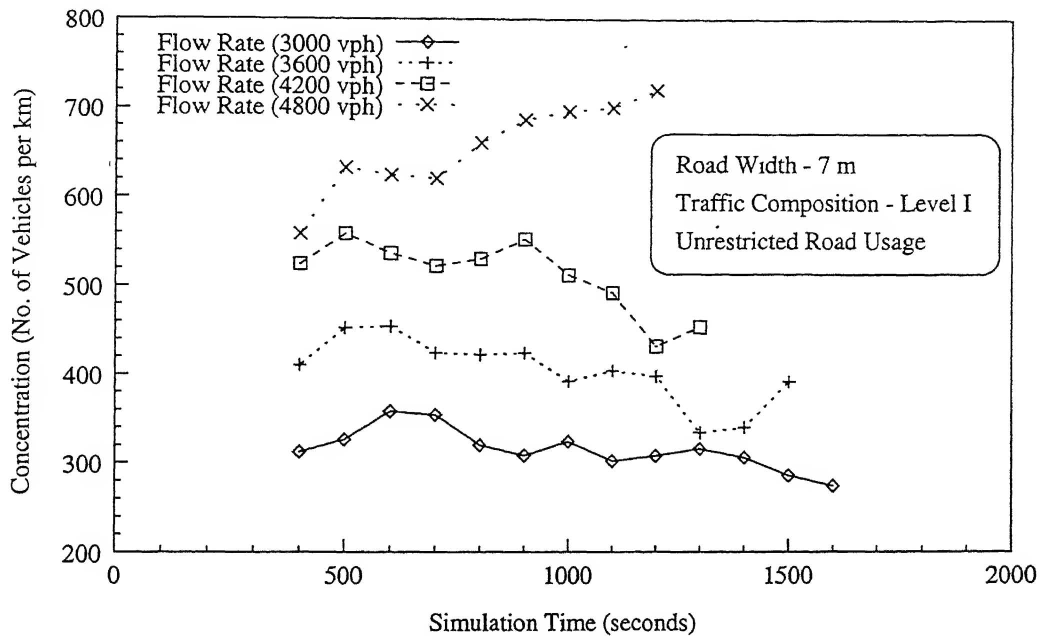


Figure 8.4: Density Time - Relationships

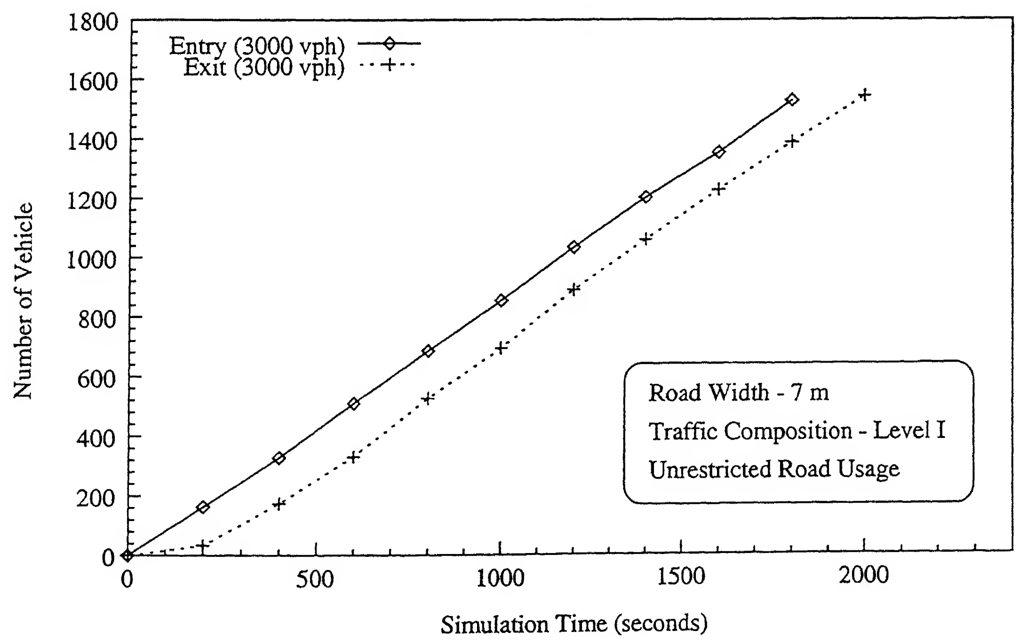


Figure 8.5: Entrance and Exit Flow Rates - Time Relationships

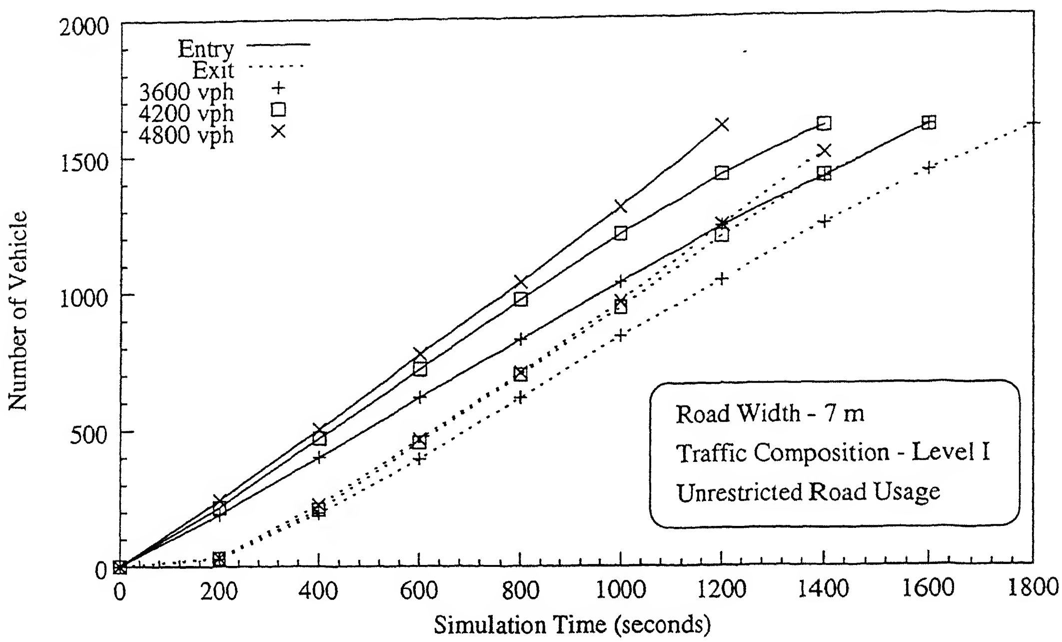


Figure 8.6: Entrance and Exit Flow Rates - Time Relationships

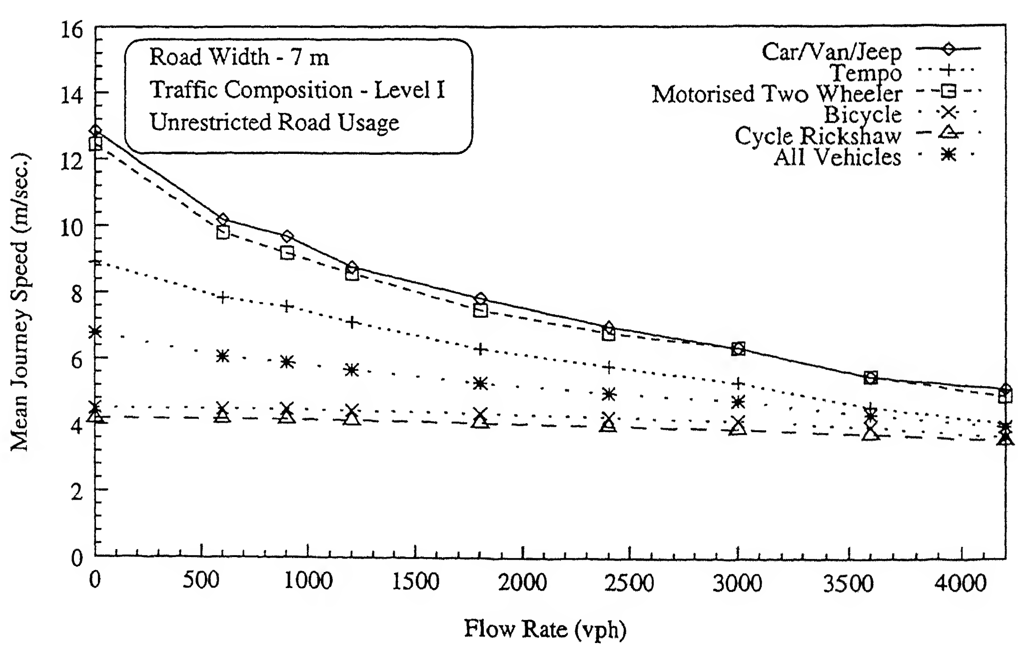


Figure 8.7: Mean Journey Speed Flow Relationships

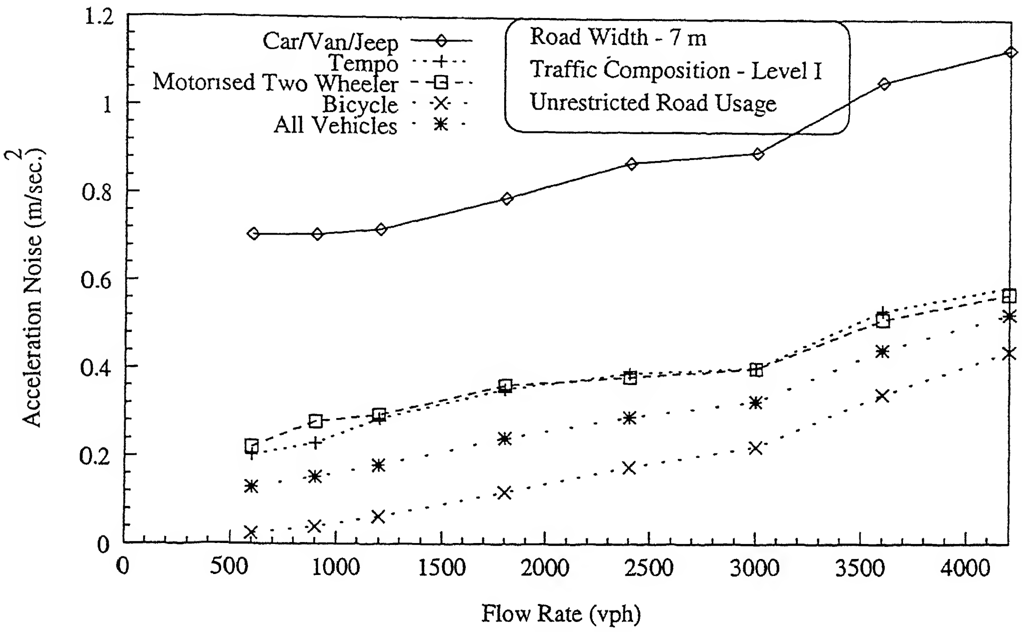


Figure 8.8: Acceleration Noise Flow Relationships

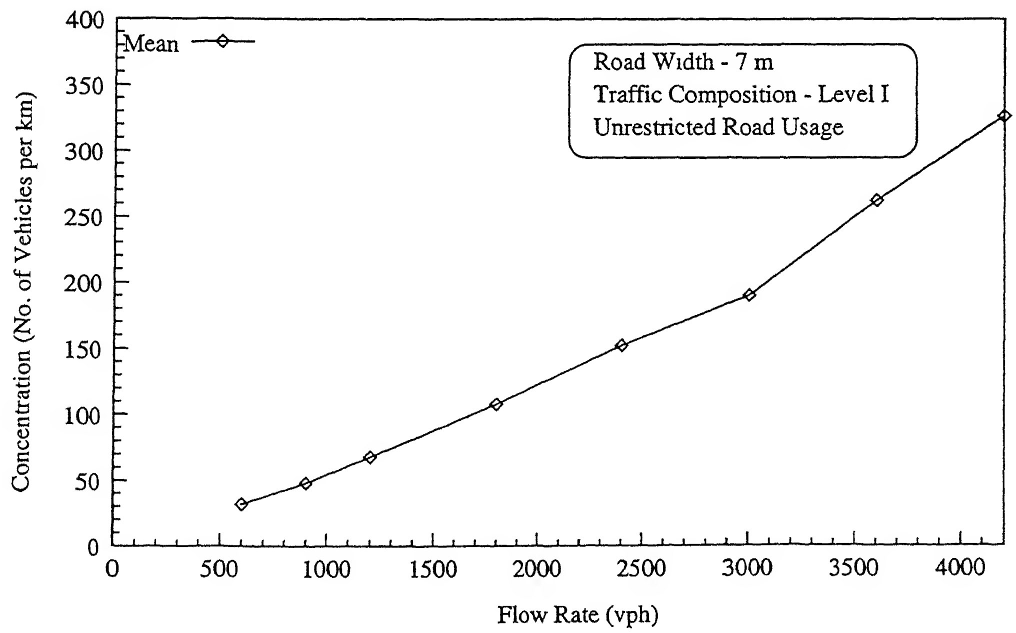


Figure 8.9: Density Flow Relationships

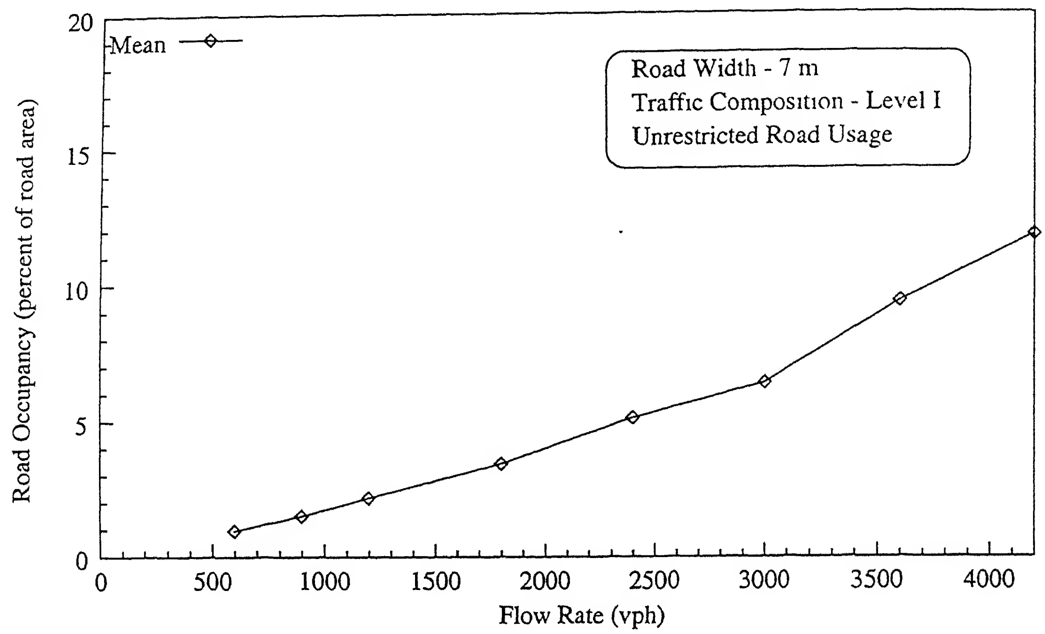


Figure 8.10: Road Occupancy Flow Relationships

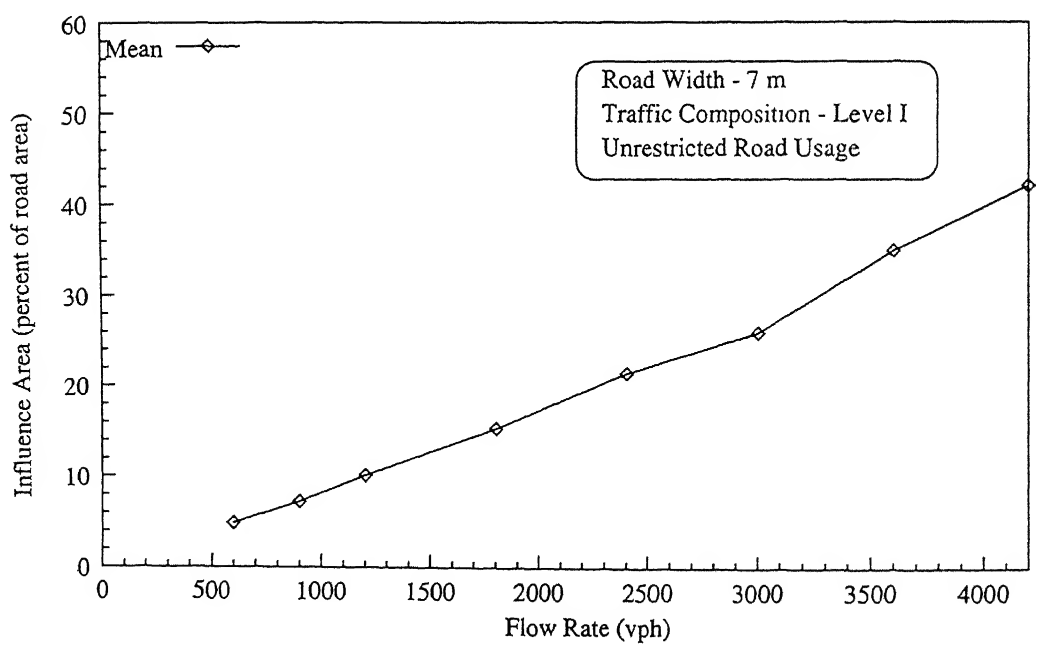


Figure 8.11: Influence Area Flow Relationships

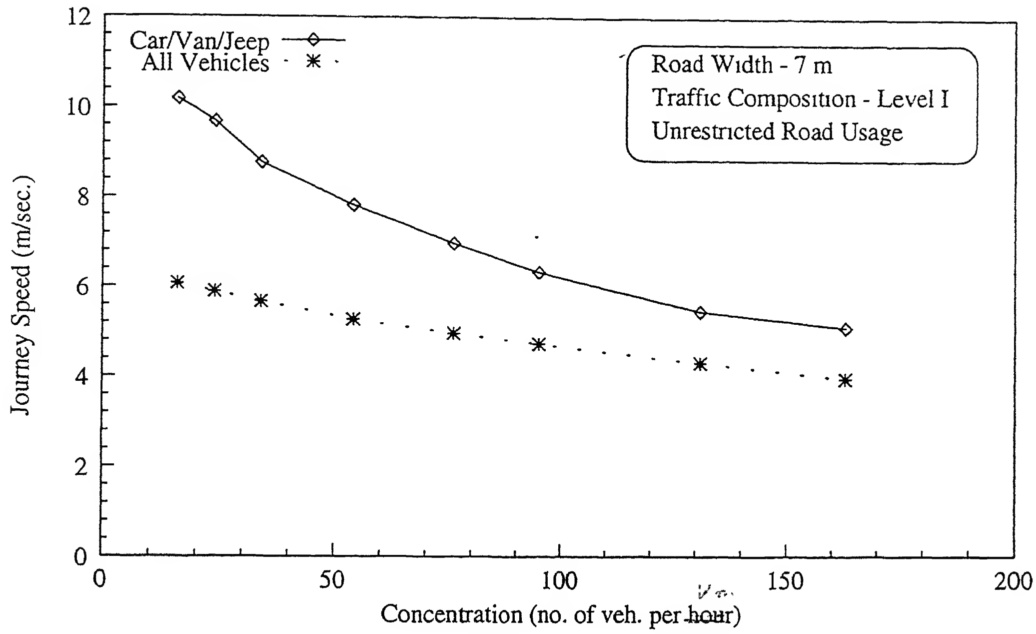


Figure 8.12: Mean Journey Speed Concentration Relationships

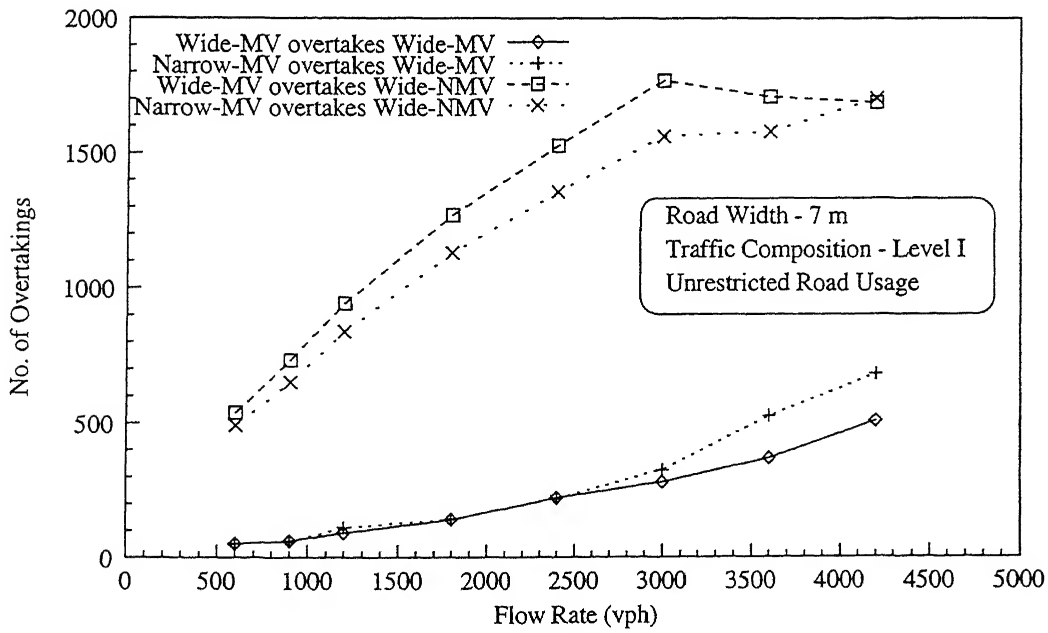


Figure 8.13: Distribution of Overtakings

Table 8.3: Mean Journey Speeds of Vehicles for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)		Journey Speed Car/ Van/ Jeep (m/sec)	Tempo/ Auto Rickshaw (m/sec)	Bus/ LCV (m/sec)	Motorised Two Wheelers (m/sec)	Bicycle (m/sec)	Cycle Rick-shaw (m/sec)	All Vehicles (m/sec)
Sample Size		80 *75	200 *186	40 *35	240 *226	800 *751	232 *220	1600 *1500
Free Speed	Mean	12.88	8.91	11.62	12.45	4.50	4.43	6.79
	St. Dev.	1.01	1.13	1.27	1.44	0.68	0.63	3.51
600	Mean	10.18	7.83	9.87	9.79	4.48	4.18	6.06
	St. Dev.	1.49	1.06	1.18	1.74	0.67	0.63	2.55
900	Mean	9.67	7.56	7.21	9.17	4.47	4.16	5.88
	St. Dev.	1.44	1.12	1.14	1.67	0.67	0.62	2.33
1200	Mean	8.76	7.10	9.00	8.56	4.43	4.13	5.66
	St. Dev.	1.43	1.07	1.28	1.58	0.66	0.62	2.07
1800	Mean	7.82	6.30	7.79	7.47	4.35	4.06	5.27
	St. Dev.	1.26	0.98	1.41	1.11	0.64	0.64	1.61
2400	Mean	6.97	5.77	6.88	6.78	4.32	3.96	4.96
	St. Dev.	0.89	0.80	1.05	0.90	0.62	0.57	1.34
3000	Mean	6.33	5.28	6.25	6.33	4.13	3.88	4.73
	St. Dev.	0.78	0.67	0.89	0.84	0.58	0.56	1.15
3600	Mean	5.46	4.54	5.18	5.47	3.93	3.73	4.31
	St. Dev.	0.67	0.59	0.68	0.73	0.54	0.51	1.15
4200	Mean	5.10	4.06	4.69	4.88	3.65	3.55	3.96
	St. Dev.	0.75	0.54	0.63	0.70	0.42	0.44	0.74

* After excluding statistics of first 100 vehicles.

Table 8.6: No. of Overtakings for Different Combinations of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

	Number of Overtakings								
Flow (vph)	Wide MV ov. Wide MV	Wide MV ov. Narrow MV	Narrow MV ov. Wide MV	Narrow MV ov. Narrow MV	Wide MV ov. Wide NMV	Wide MV ov. Narrow NMV	Narrow MV ov. Wide NMV	Narrow MV ov. Narrow NMV	Total
600	51	9	53	9	538	1481	491	1203	5064
900	61	20	58	24	732	2126	650	1722	7201
1200	91	12	111	16	942	2611	836	2219	9255
1800	140	41	142	40	1268	3432	1128	2941	12757
2400	220	46	218	64	1526	4192	1353	3641	16032
3000	279	55	324	72	1768	4372	1561	4160	18386
3600	367	65	524	125	1708	4279	1578	4402	19634
4200	506	108	680	167	1687	4374	1702	4731	20694

MV : Motorised Vehicle, NMV : Non-Motorised Vehicle, ov. : Overtakes.

and traffic composition (Level I), the following operating characteristics may be considered to define the LOS.

Journey Speed of Cars As cars have the highest free speed, they encounter lot of interactions. This speed is significantly affected by the flow level.

Journey Speed of Motorised Two Wheelers The free speed of these vehicles is slightly lower than that of cars. As these vehicles are narrow they are able to perform more manoeuverings in the heterogeneous traffic mix. Further the proportion of these vehicles is also significant in the traffic mix. The journey speed of non-motorised vehicles do not really define the quality of service as they are able to move at speeds close to the free speeds.

Concentration Concentration defined in terms of number of vehicles per km defines the longitudinal spacing between the vehicles. Ability to overtake/pass depends upon the spacing between the vehicles in its neighbourhood. Congestion is directly defined by the concentration level.

Road Occupancy This is the physical area of the vehicles in the road section relative to the road area. This measure is adopted as the vehicles of heterogeneous traffic mix have wide variations in their dimensions.

Considering the nature of simulation results with reference to different operating characteristics, the performance can be classified into the following four groups.

LOS I This is the level for reasonably free flow conditions and operates upto a maximum service volume of 600 vph. The mean journey speeds of cars and motorised two wheelers is upto 80 percent of their free speeds, i.e., cars-10.30 m/sec (37 kmph) and motorised two wheelers 10.0 m/sec (36 kmph). The average longitudinal spacing is about 65 metres with a density of 30 vehicles per km. The vehicle area occupied (road occupancy) is just about 1 percent of the total road area.

LOS II Flow conditions are stable and operate upto maximum service volume of 1800 vph. The average operating speed of cars and motorised two wheelers lies between 60-80 percent of their free speed, i.e., cars 7.7 m/sec (28 kmph) and motorised two wheelers 7.5 m/sec (27 kmph). The average longitudinal spacing is just 20 metres with a concentration of 100 vehicles per km and the average road occupancy is 3.5 percent of the total road area.

LOS III Increase in flow level significantly deteriorates the service. The difference in the operating speeds of car and non-motorised vehicles considerably narrows down. At the maximum service volume of 3000 vph, the operating speed of cars and motorised two wheelers is only 50 percent of their free speeds, i.e., cars 6.4 m/sec (23 kmph) and motorised two wheelers 6.2 m/sec (22 kmph). The maneuverability is seriously limited due to high proportion of constrained flow. The average longitudinal spacing is about 11 metres with a density of 180 vehicles per km. The vehicle road occupancy increases to 6.5 percent of road space.

LOS IV Flow conditions are unstable and operate upto maximum volume of 4200 vph. The mean travel speed of cars and motorised two wheelers at maximum service volume is just 40 percent of their free speed, i.e., cars 5.20 m/sec (19 kmph) and motorised two wheelers 5.0 m/sec (18 kmph). Manoeuvrability gets seriously affected as gaps are small to allow overtakings and passings . Average longitudinal spacing is just about 6 metre, with density of 320 vehicles per km. The road occupancy level increases to 12 percent.

Table 8.7 summarises the numerical value of operating characteristics for the four levels of service. The maximum possible flow for each LOS is also specified. Though the descriptions of LOS are specified with numerical values, it may be emphasized that a certain amount of subjectivity is involved because of large number of variables coming into play.

8.4.2 Mathematical Relationships for Traffic Stream Characteristics

The study of simulation results show that the model performance measures are quite logical and replicate real life traffic operation. It is also observed that performance measures show definite trends with flow rates and could be suitably modelled. Mathematical relationships have been estabilshed for the performance measures as given in Table 8.8. Second order polynomials are fitted to relate the performance measures with the flow levels for benchmark road (Road - I) and traffic composition level I with unrestricted non-motorised vehicle road usage. The relation is of form

$$y = a_0 + a_1 q + a_2 q^2 \tag{8.1}$$

where y = value of performance measure
q = flow level
a_0, a_1, a_2 = value of coefficients

Table 8.7: Level of Service for 7 m Wide Road, Traffic Composition of Level I´and Unrestricted Road Usage for Non-motorsied Vehicles

Level of Service (LOS)	I	II	III	IV
Maximum Service Flow (MSF) (vph)	600	1800	3000	4200
Cars				
Free Speed (m/sec)	12.88			
Travel Speed (m/sec) Travel Speed (percent of free speed)	10.30 ≥80	7.73 ≥60	6.44 ≥50	5.15 ≥40
Motorised Two Wheelers				
Free Speed (m/sec)	12.45			
Travel Speed (m/sec) Travel Speed (percent of free speed)	9.96 ≥80	7.47 ≥60	6.23 ≥50	5.0 ≥40
Density (veh/km)	≤30	≤100	≤180	≤320
Road Occupancy (percent of road area)	≤1.0	≤3.5	≤6.5	≤12.0

The relationships for benchmark road (Road - I) and traffic composition of level I with unrestricted road usage of non-motorised vehicles are given in Table 8.8.

8.5 ANALYSIS OF SIMULATION RESULTS FOR ROAD WITH RESTRICTION ON USE OF ROAD SPACE BY NON-MOTORISED VEHICLES

The movement of non-motorised vehicles in this road is restricted to only one lane (3.5 m) adjacent to the road kerb. The motorised vehicles will predominantly use the other lane but may also use the lane on which non-motorised vehicles are restricted. The motorised vehicles in this case will have more interactions among themselves. The speed of the interacting motorised vehicles is likely to be higher than when they interact with slow moving non-motorised vehicles. The statistics for different performance measures at varying flow levels are presented in Tables C.1 to C.4 of Appendix C. The variation of different performance measures with flow level are shown in Figures 8.14 to 8.21. To study the impact of restricting

Table 8.8: Mathematical Relationships for Performance Measures

Road I (7 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

Performance Measure	Relation Coefficients		
	a_0	a_1	a_2
Mean Journey Speeds			
Car/Van/Jeep (U_{cj})	12.88	-0.00368	4.52891e-07
Tempo/Auto Rickshaw (U_{te})	8.91	-0.00160	1.10061e-07
Bus/LCV (U_{bl})	11.62	-0.00290	3.16095e-07
Motorised Two Wheeler (U_{mt})	12.45	-0.00355	4.42255e-07
Bicycle (U_{bi})	4.50	3.25298e-05	-5.42288e-08
Cycle Rickshaw (U_{cr})	4.43	-0.00023	9.33613e-09
All Vehicles (U_{av})	6.79	-0.00098	7.90077e-08
Acceleration Noise			
Car/Van/Jeep (AN_{cj})	0.00	0.00066	-1.01682e-07
Tempo/Auto Rickshaw (AN_{te})	0.00	0.00024	-2.52083e-08
Bus/LCV (AN_{bl})	0.00	0.00087	-1.45859e-07
Motorised Two Wheeler (AN_{mt})	0.00	0.00025	-3.12369e-08
Bicycle (AN_{bi})	0.00	2.70367e-05	1.82389e-08
Cycle Rickshaw (AN_{cr})	0.00	3.97353e-05	1.3491e-08
All Vehicles (AN_{av})	0.00	0.00014	-5.41141e-09
Traffic Density			
Mean Density (K_{mean})	0.00	0.04396	7.82295e-06
Maximum Density (K_{max})	0.00	0.07437	1.24336e-06
Road Occupancy			
Mean Road Occupancy (RO_{mean})	0.0	0.00120	3.76295e-07
Maximum Road Occupancy (RO_{max})	0.0	0.00312	-2.13446e-08
Influence Area			
Mean Influence Area (IFA_{mean})	0.0	0.00723	6.51684e-07
Maximum Influence Area (IFA_{max})	0.0	0.01465	-1.12975e-06
Number of Overtakings/Passings ($NOVRT$)	0.00	8.89182	-0.000944

road usage these figures also include the performance measures of Benchmark Road with unrestricted non-motorised vehicle road usage. The comparison demonstrates the following observations:

- For restricted road usage, the journey speed of motorised vehicles are higher than those incase of unrestricted road usage. The journey speeds of motorised vehicles are higher by about 1.0-1.5 m/sec (3.6-5.4 kmph) during the stable state condition.
- Restricted road usage has no significant change in the journey speeds of non-motorised vehicle.
- Like the unrestricted case, this road also produces unstable flow state beyond flow level of 4200 vph. This shows that road capacity is not affected by road usage restriction.
- As interactions are mostly amongst the motorised vehicles and these have higher journey speeds, the acceleration noise is less than case of unrestricted road usage.
- The number of overtakings/passings are also higher as motorised vehicles are not constrained by slow moving non-motorised vehicles.
- Concentration (number of vehicles) are almost identical for both cases. However, the road occupancy and the influence area are slightly less in case of unrestricted road usage.
- Based on the criteria established for defining the level of service (Table 8.7), it is observed that due to higher journey speeds of motorised vehicles, the maximum service flows for some levels of service will be higher. The estimated maximum service flows are 1000, 2400, 3600, and 4200 vph for levels of service LOS I, II, III and IV respectively (Table 8.9).

This study of simulation results show that developed simulation model is sensitive to the restriction in road usage of different vehicle types and is close to real traffic flow process.

8.6 ANALYSIS OF SIMULATION RESULTS FOR DIFFERENT TRAFFIC COMPOSITIONS

Traffic composition of level I for benchmark road has 35 percent of motorised vehicles and 65 percent of non-motorised vehicles. To study the sensitivity of traffic composition, the simulation runs for two other levels (Level II and Level III) are made. Traffic composition level II has equal share of motorised and non-motorised vehicles, whereas traffic composition of level III has 65 percent of motorised vehicles. The statistics for different performance measures for various flow levels are presented in Tables C.5 to C.12 of Appendix C for traffic

Table 8.9: Maximum Service Flows at Different Levels of Service

Classification	Maximum Service Flow (vph)			
	LOS-I	LOS-II	LOS-III	LOS-IV
Road Width - 7.0 m (Road - I) Traffic Compositiom - Level I NMV road usage unrestricted	600	1800	3000	4200
Road Width - 7.0 metre (Road - I) Traffic Composition - Level I NMV road usage restricted to 3.50 m	1000	2400	3600	4200
Road Width - 7.0 m (Road - I) Traffic Composition - Level II NMV road usage unrestricted	900	2100	3100	3600
Road Width - 7.0 m (Road - I) Traffic Composition - Level III NMV road usage unrestricted	900	2100	3000	3500
Road Width - 10.0 m (Road II) Traffic Composition - Level I NMV road usage unrestricted	900	2700	4500	5400
Road Width - 14.0 m (Road III) Traffic Composition - Level I NMV road usage unrestricted	1200	3600	5800	6600

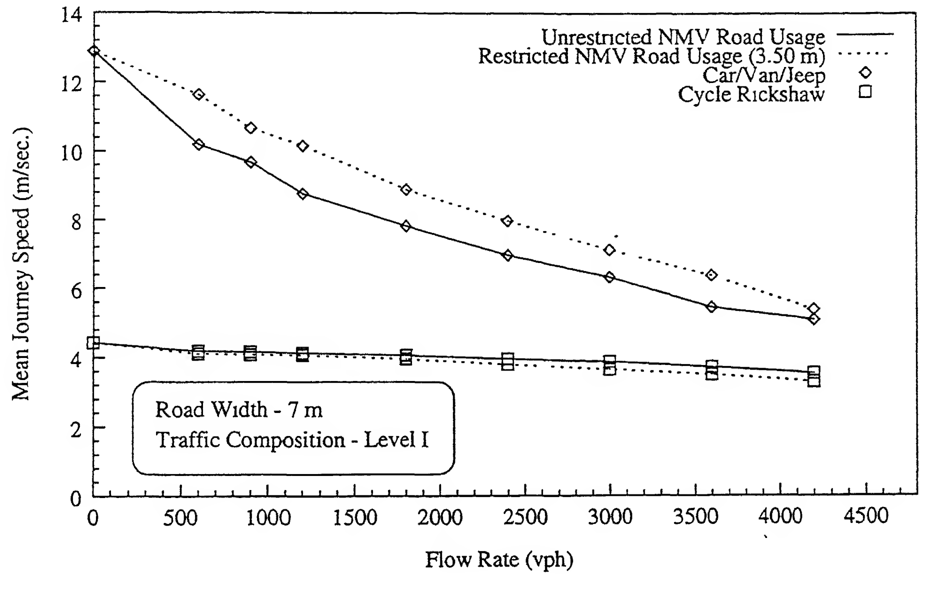


Figure 8.14: Mean Journey Speed Flow Relationships for Restricted and Unrestricted NMV Road Usage

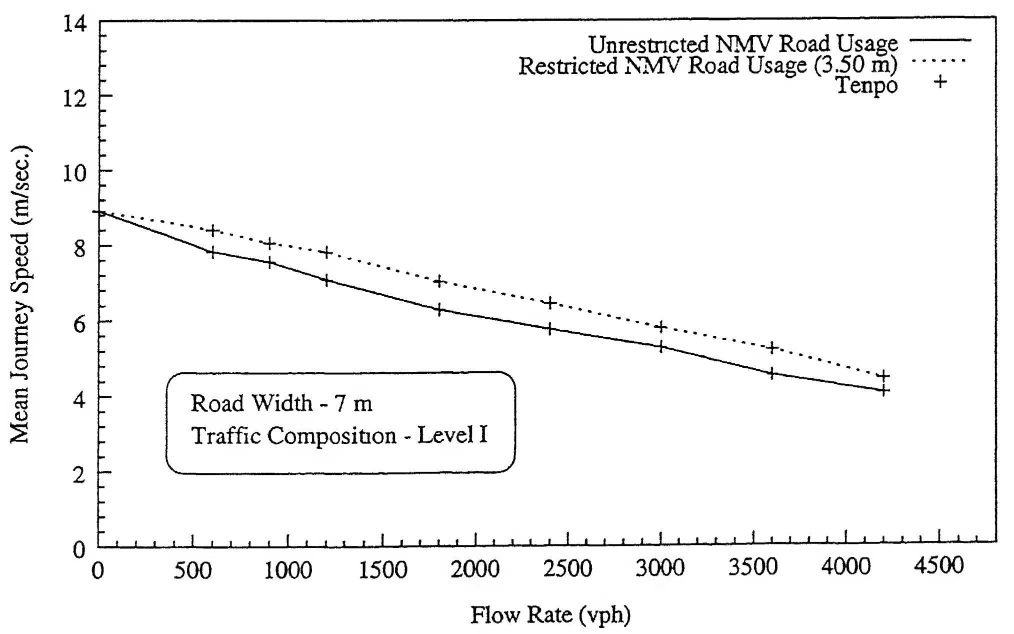


Figure 8.15: Mean Journey Speed Flow Relationships for Restricted and Unrestricted NMV Road Usage

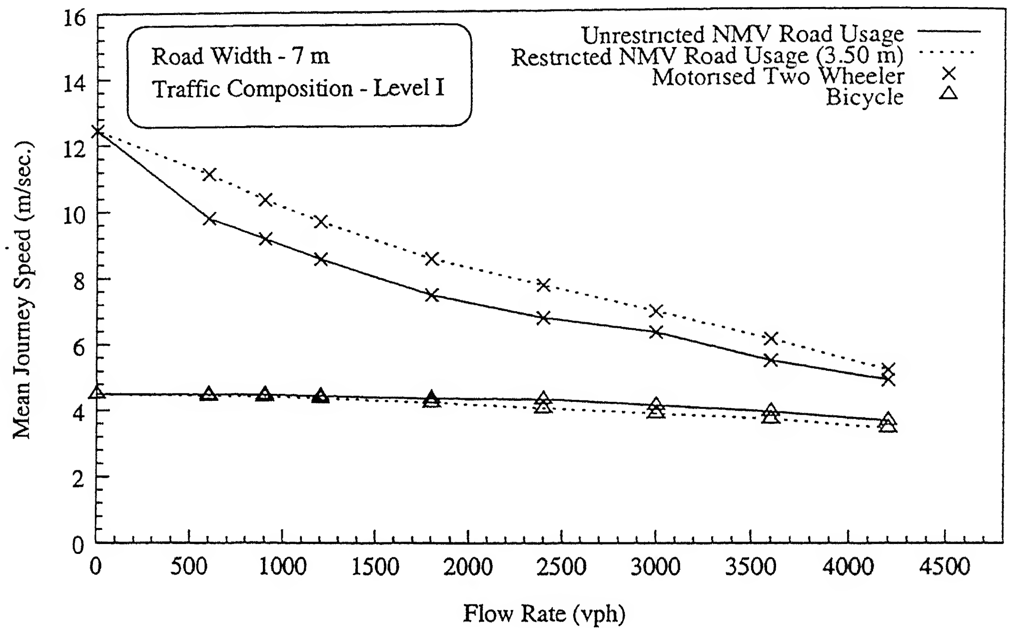


Figure 8.16: Mean Journey Speed Flow Relationships for Restricted and Unrestricted NMV Road Usage

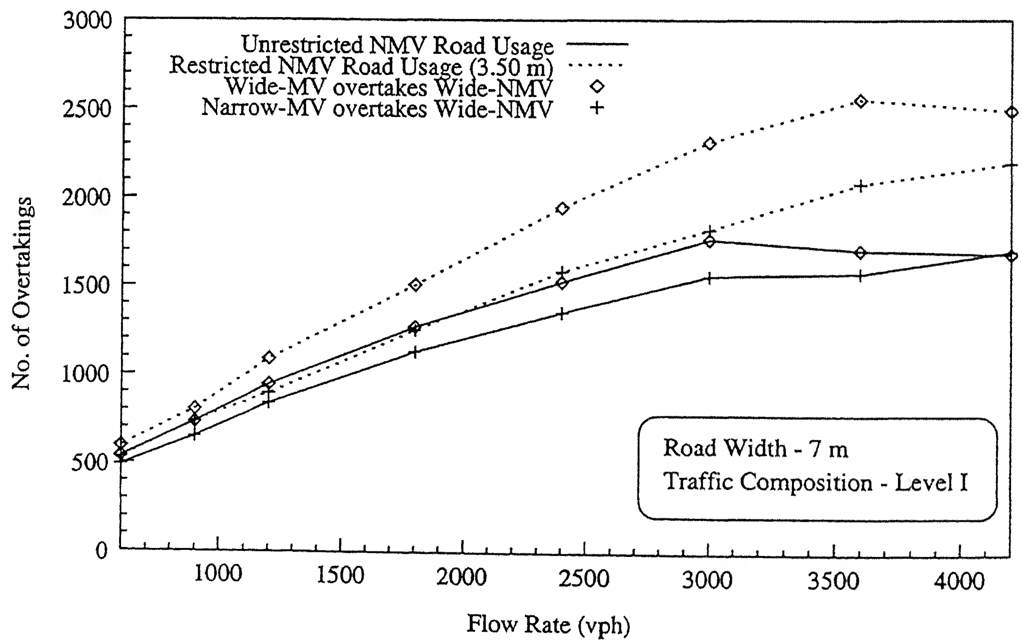


Figure 8.17: Distribution of Overtakings for Restricted and Unrestricted NMV Road Usage

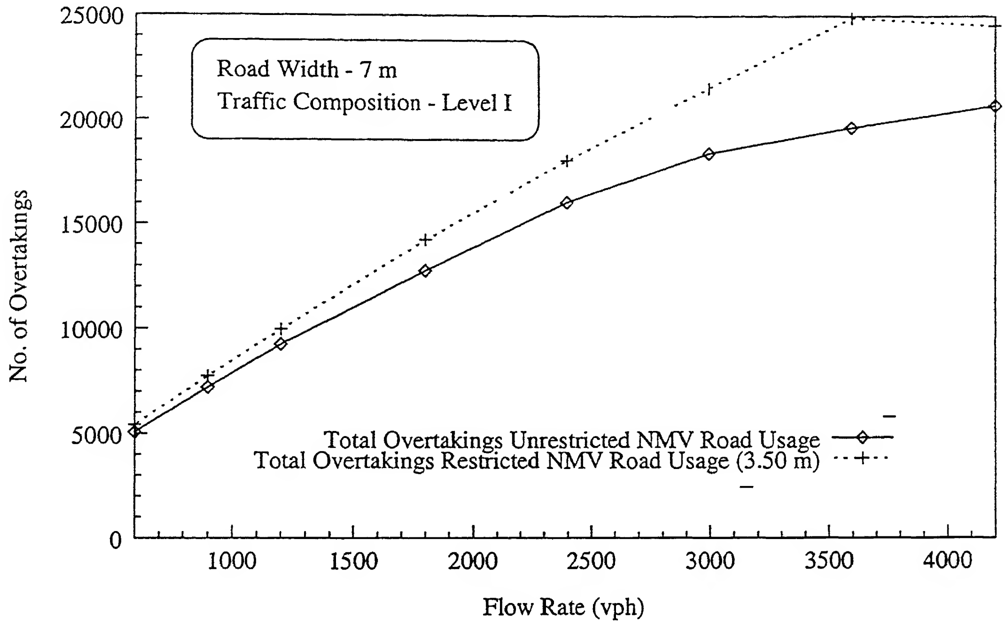


Figure 8.18: Distribution of Overtakings for Restricted and Unrestricted NMV Road Usage

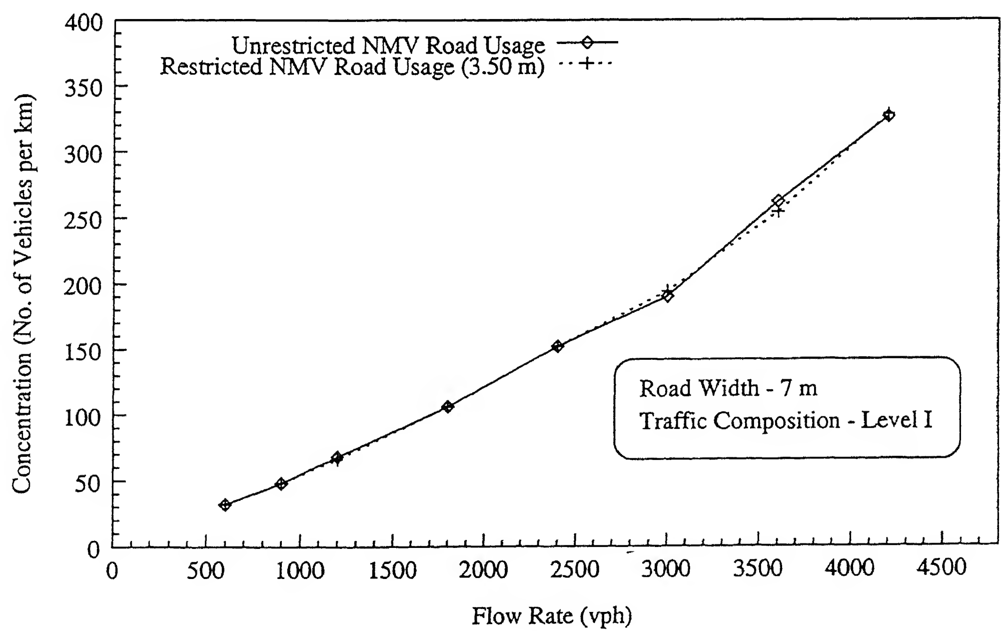


Figure 8.19: Density Flow Relationships for Restricted and Unrestricted NMV Road Usage

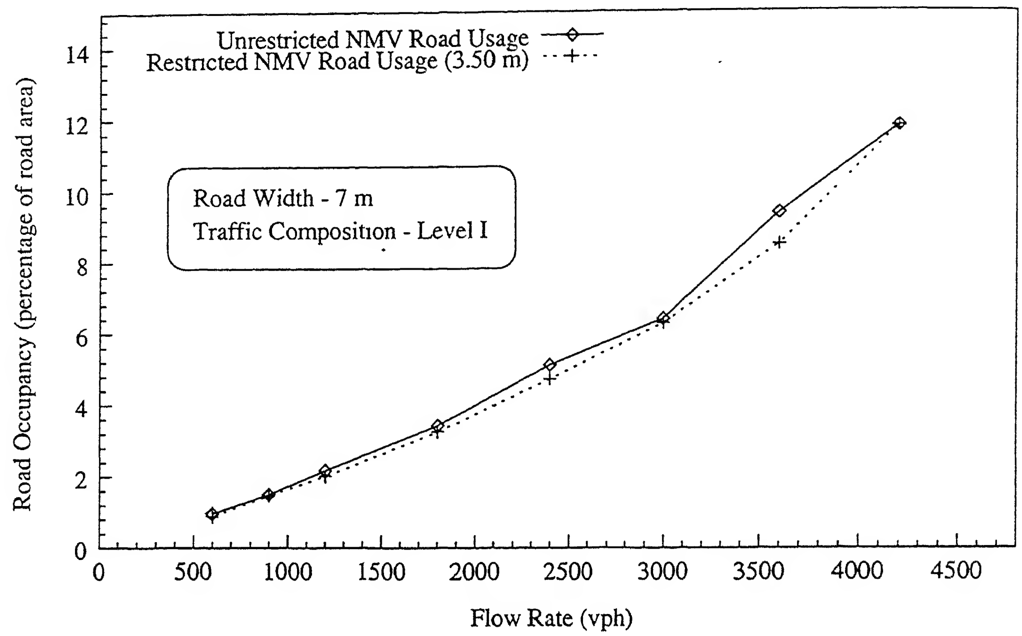


Figure 8.20: Road Occupancy Flow Relationships for Restricted and Unrestricted NMV Road Usage

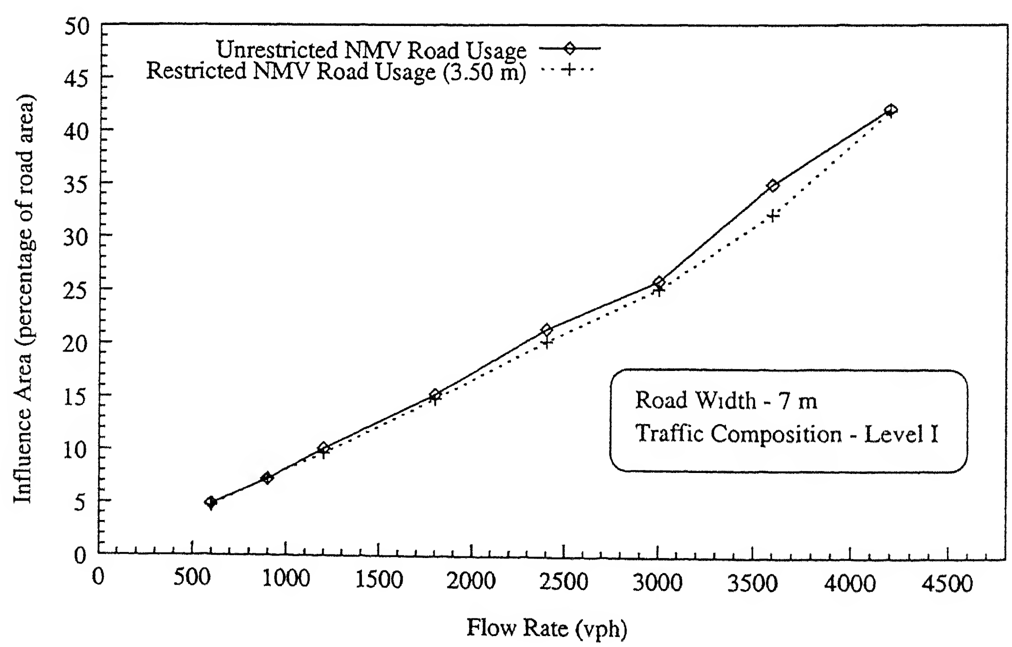


Figure 8.21: Influence Area Flow Relationships for Restricted and Unrestricted NMV Road Usage

compositions of level II and level III. The variation of different performance measures with flow are shown in Figures 8.22 to 8.28 for all the three traffic compositions. Comparison of the different composition levels indicate the following:

- The motorised vehicles have longer influence length (both head length and tail length). When the proportion of motorised vehicles is high (traffic composition level III), the unstable flow state is expected to occur at flow level less than the case of Level I traffic composition. It is observed that for traffic composition of level II, the road capacity could be only 3600 vph. While for traffic composition of level III, it is of the order of 3500 vph. These values are much less than that of traffic composition of level I, which has capacity of 4200 vph.

- The journey speeds of motorised vehicles for traffic composition of level II and III are higher than those for traffic composition level I upto flow level of 3000 vph. The difference between the journey speeds for traffic composition level II and III are very marginal. Beyond flow level of 3500 vph the journey speeds of level II and III are even less than level I because of unstable state.

- The concentration for level II and III are less than that of level I because of longer influence length of motorised vehicles. However, the percentage road occupancy and percentage influence area are highest for level III traffic composition.

- Number of overtakings performed by motorised vehicles are higher for traffic composition level II and III than level I. This is because the number of motorised vehicles are more in traffic composition level II and level III as compared to level I.

- The total number of overtakings performed by all vehicles are least for traffic composition level III. As level III has more number of motorised vehicles, the number of overtakings amongst them is bound to be less.

- Based on the criteria established for defining levels of service, it is estimated that the maximum service flow for traffic composition level II and III are higher with reference to levels of service LOS - I, II and III. However, for level of service LOS - IV, which corresponds to unstable state, the maximum service flow level is less for composition level II and III. The estimated maximum service flow for the four levels of service are 900, 2100, 3100, and 3600 vph for traffic composition level II, while the corresponding values for traffic composition level III are 900, 2100, 3000, and 3500 vph. (Table 8.9)

The analysis of the simulation results have shown that the simulation model is sensitive to the movement of motorised and non-motorised vehicles in the heterogeneous traffic mix. The results are like the real traffic movement process.

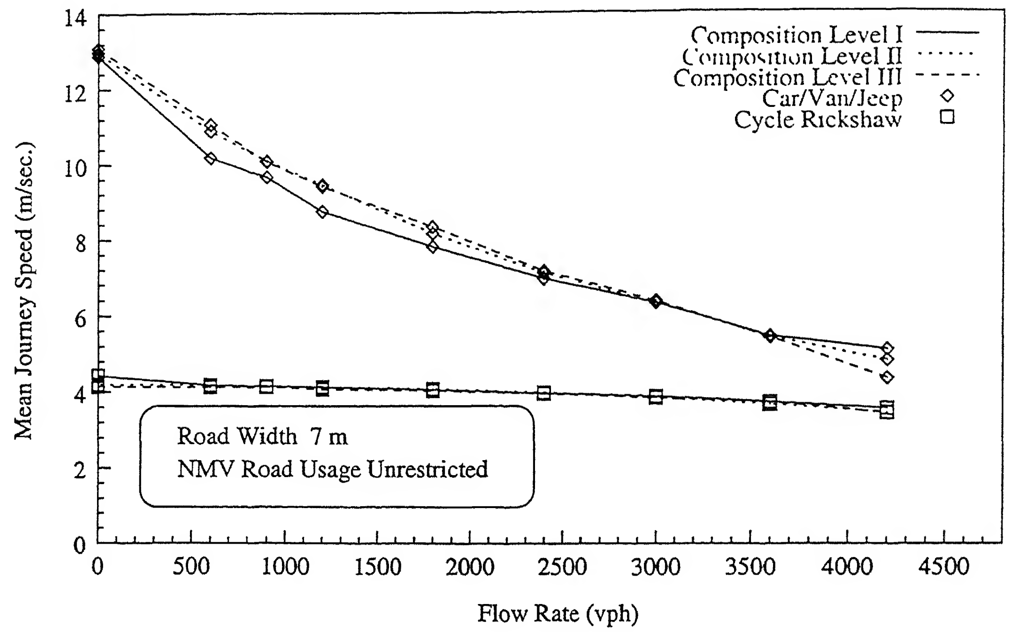


Figure 8.22: Mean Journey Speed Flow Relationships for Different Levels of Traffic Composition

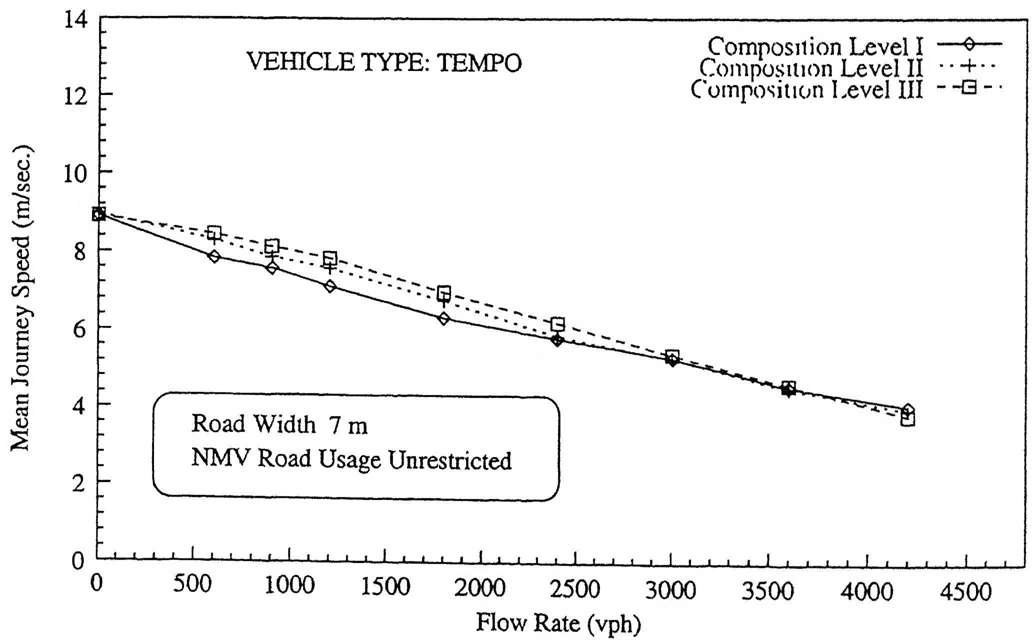


Figure 8.23: Mean Journey Speed Flow Relationships for Different Levels of Traffic Composition

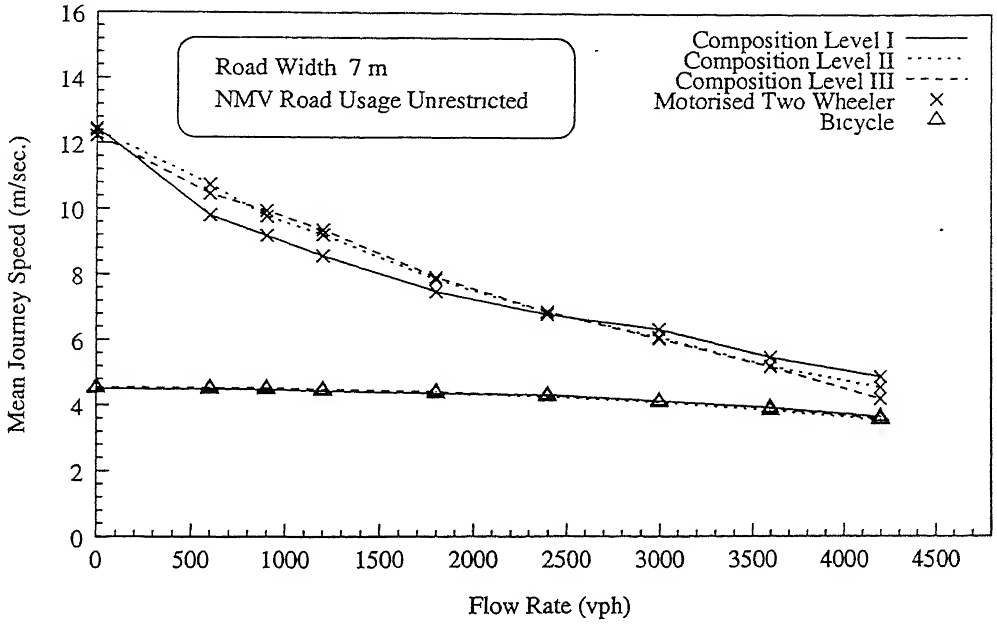


Figure 8.24: Mean Journey Speed Flow Relationships for Different Levels of Traffic Composition

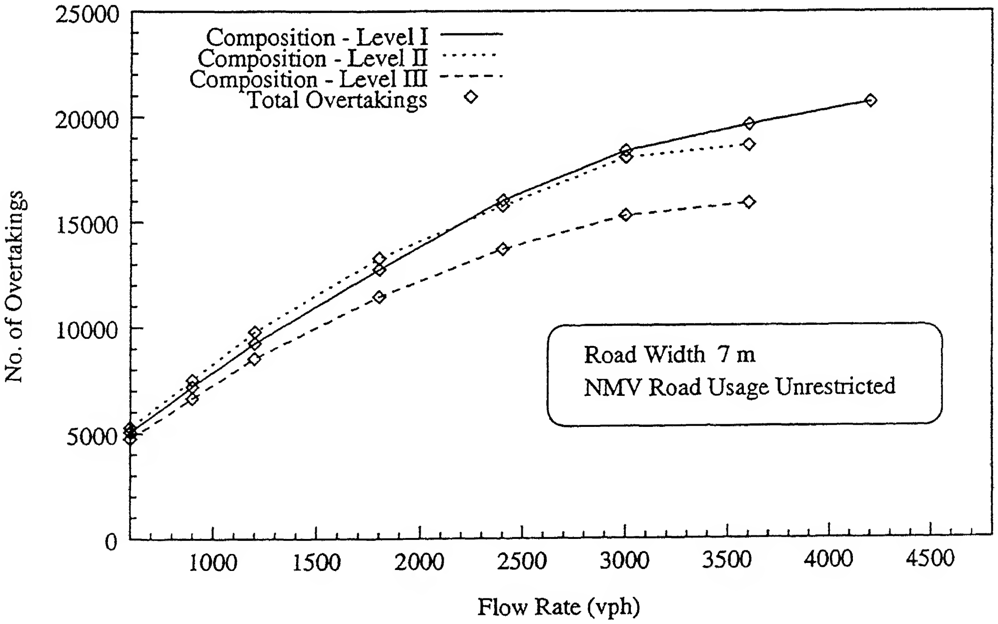


Figure 8.25: Distribution of Overtakings for Different Levels of Traffic Composition

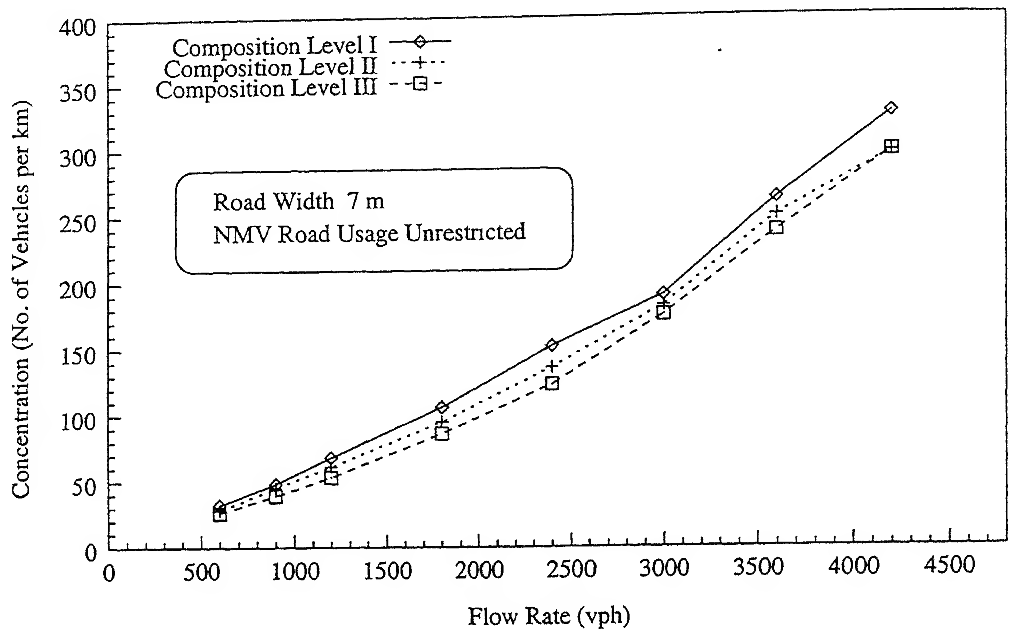


Figure 8.26: Density Flow Relationships for Different Levels of Traffic Composition

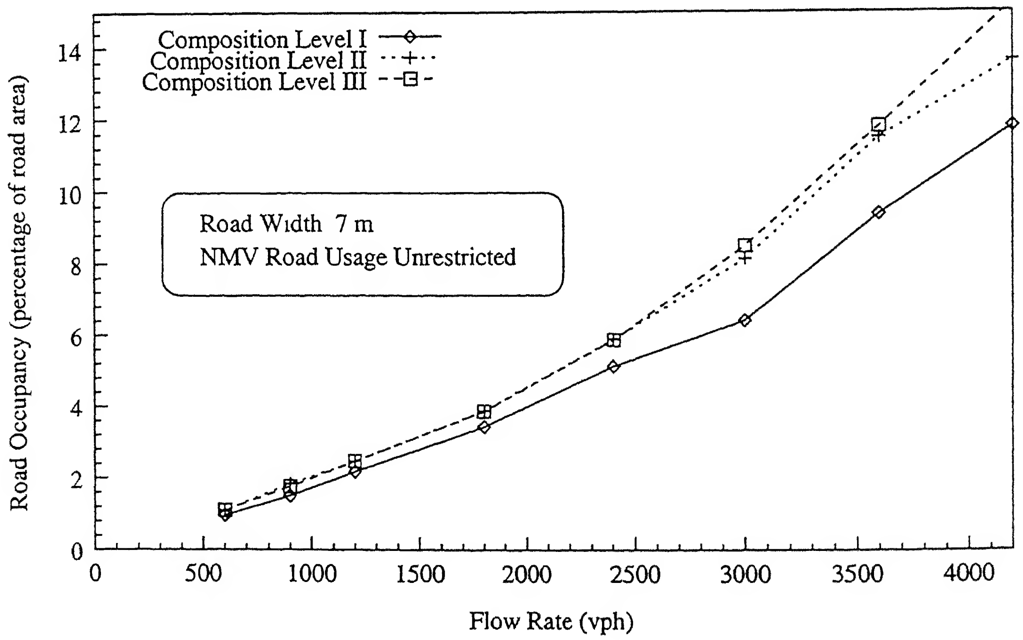


Figure 8.27: Road Occupancy Flow Relationships for Different Levels of Traffic Composition

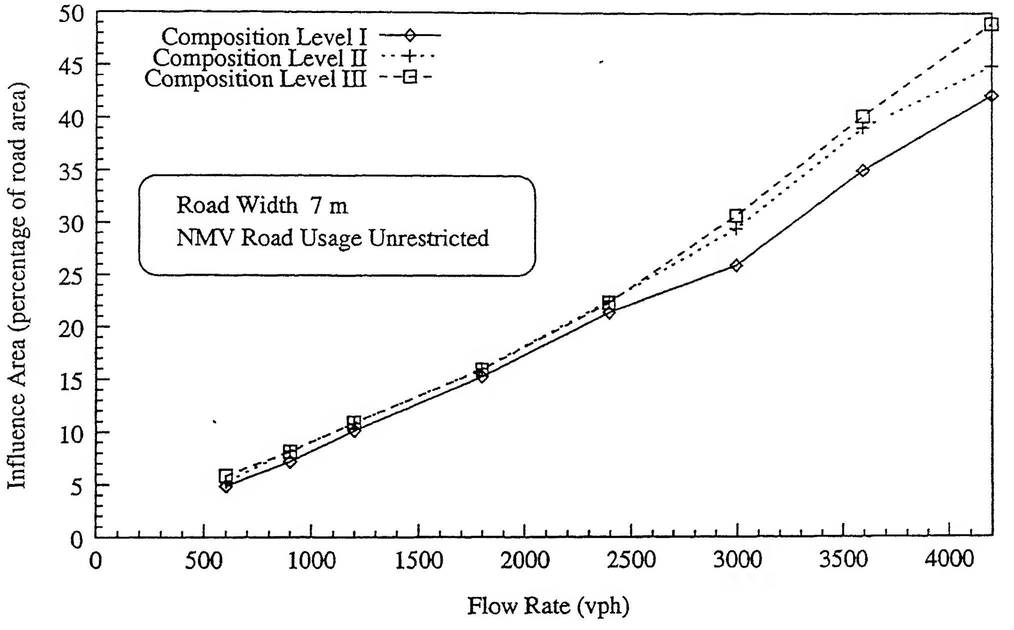


Figure 8.28: Influence Area Flow Relationships for Different Levels of Traffic Composition

8.7 ANALYSIS OF SIMULATION RESULTS FOR DIFFERENT ROAD WIDTHS

To study the sensitivity of the simulation model, traffic on different road widths are simulated. Simulation experiments are made for three different road widths of 7, 10 and 14 metre. Traffic composition for all the three cases is of level I with unrestricted road usage of non-motorised vehicles. Increase in road width enables vehicles to have more spacing and high travel speed. The statistics of different performance measures like journey speed, number of overtakings/passings, acceleration noise, and concentration (number of vehicles, percent road occupancy, and percent influence area) are presented in Tables C.13 to C.20 of Appendix C. The variation of different performance measures with flow are shown in Figures 8.29 to 8.36. The study of performance measures demonstrates the following observations:

- For the 7 m wide road, unstable state is observed at flow level of 4200 vph. For the 10 metre wide road, flow is unstable beyond level of 5400 vph, while for 14 metre width, the road capacity is 6600 vph (Table 8.9). These levels are estimated based on the variation of speed and concentration over time.
- The journey speed at a particular flow level is higher for wider roads. The difference

in journey speeds also increases with flow level.

- At low flow levels, vehicles move at speeds close to their free speed in all the three road widths. At high flow levels the mean journey speed for 14 metre road is about 4 m/sec (15 kmph) higher than that of 7 metre road.
- The journey speeds of non-motorised vehicles are also high for wider roads, but this difference is significant at very high flow levels.
- As the flow level increases, there are more traffic interactions in the form of desired overtakings/passings. For wide roads overtakings/passings manoeuvers could be performed, whereas for 7 metre road, the vehicles may have to move in the constrained flow situation. This results in higher speed for the wider roads.
- The number of overtaking/passing operations are significantly higher for the 14 metre wide road as compared to 7 metre wide road.
- The traffic concentration, road occupancy, and influence area are less for wider roads due to increased journey speed.
- Based on the criteria established for defining level of service, it is estimated that the maximum service flow for unstable state are 5400 and 6600 vph for roads of 10 and 14 metre width respectively. The estimated maximum service volume for the different levels of service are presented in Table 8.9. The maximum service volume for level of service I is 1200 vph for 14 m wide road. For the four levels of service, the estimated maximum service flow are 900, 2700, 4500, and 5400 vph for 10 metre wide road, while the corresponding values for 14 metre wide road are 1200, 3600, 5800, and 6600 vph.

The study of the above simulation results clearly demonstrates the capability of simulation model to simulate traffic over different road widths. As the simulation model does not make use of any lane concept, it is possible to simulate realistically the flow on any effective road width of Indian urban roads.

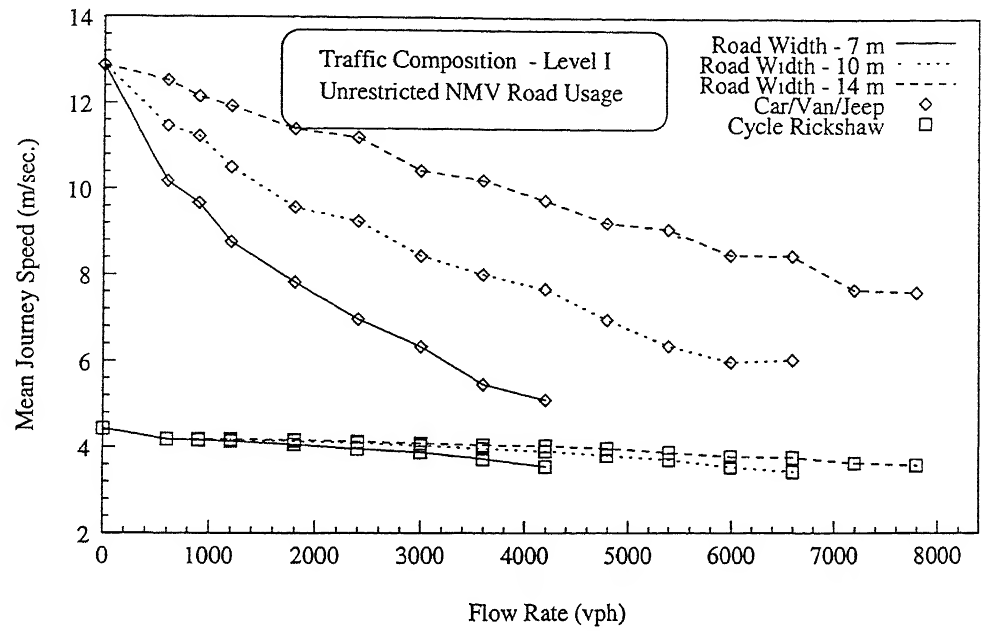


Figure 8.29: Mean Journey Speed Flow Relationships for Different Road Widths

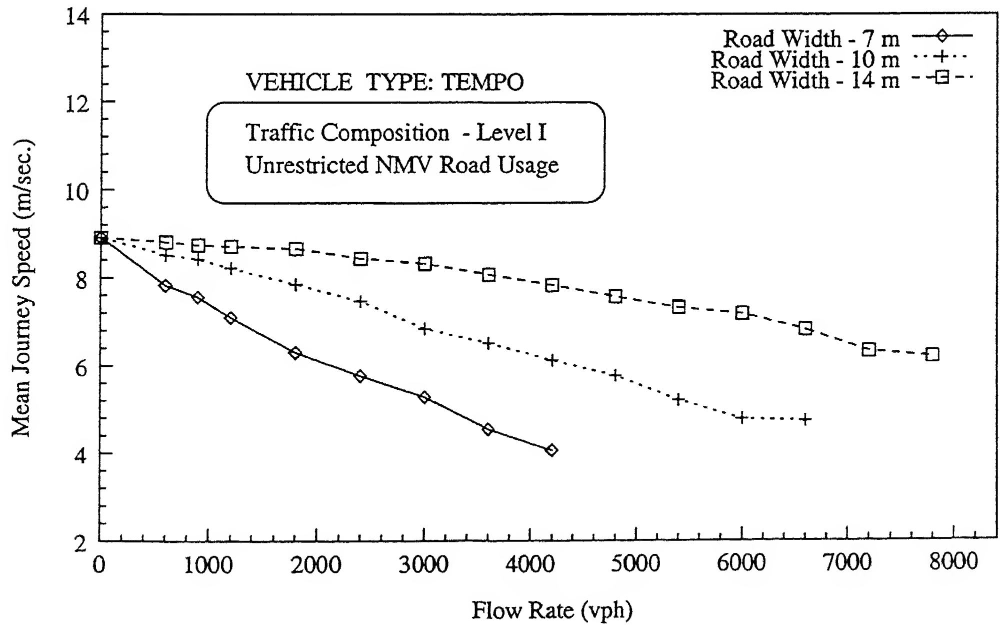


Figure 8.30: Mean Journey Speed Flow Relationships for Different Road Widths

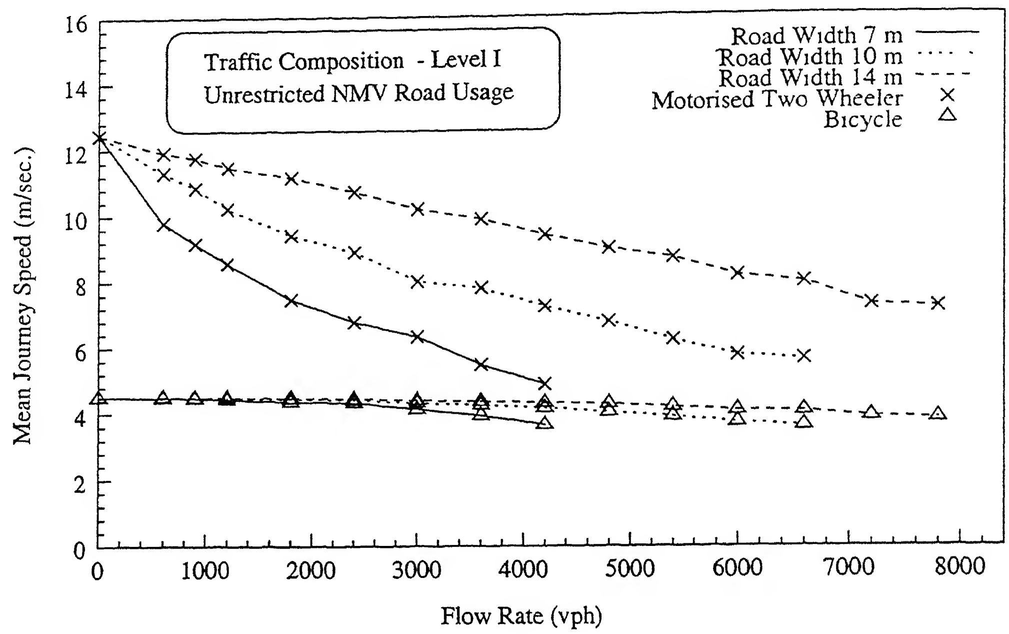


Figure 8.31: Mean Journey Speed Flow Relationships for Different Road Widths

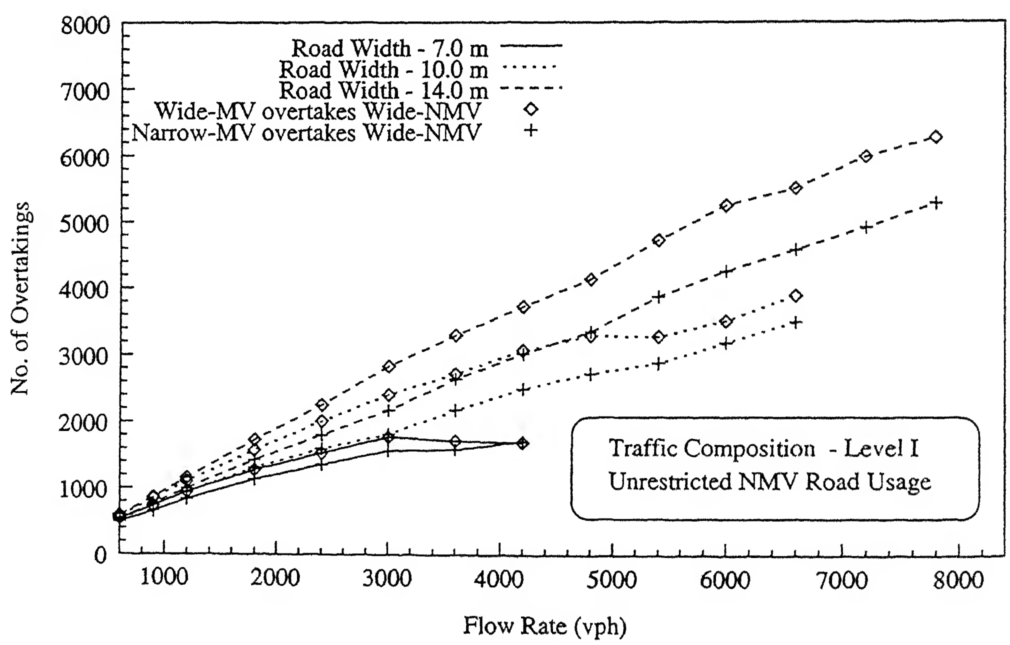


Figure 8.32: Distribution of Overtakings for Different Road Widths

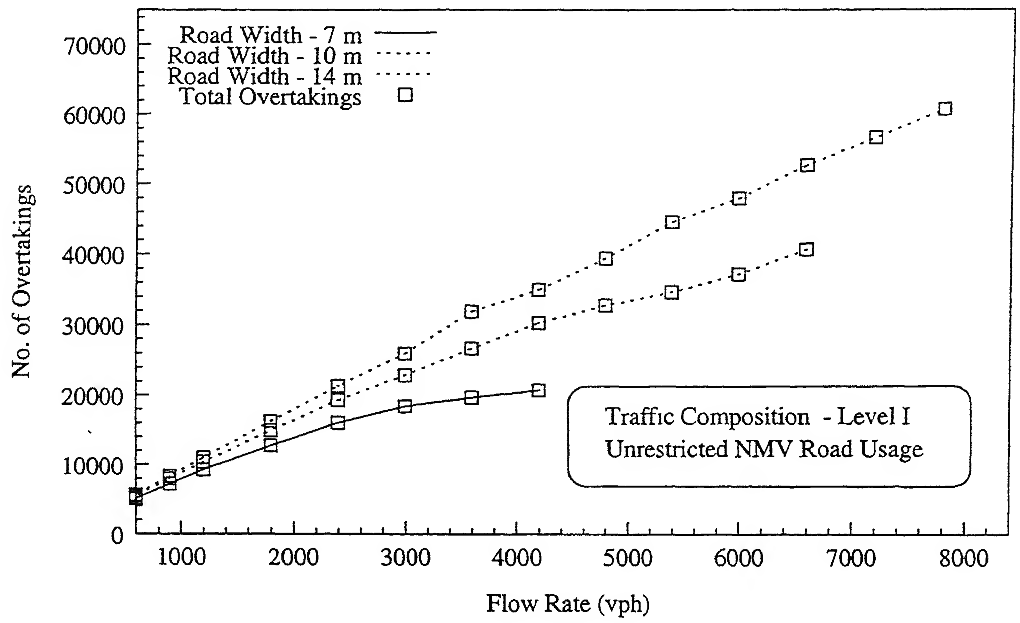


Figure 8.33: Distribution of Overtakings for Different Road Widths

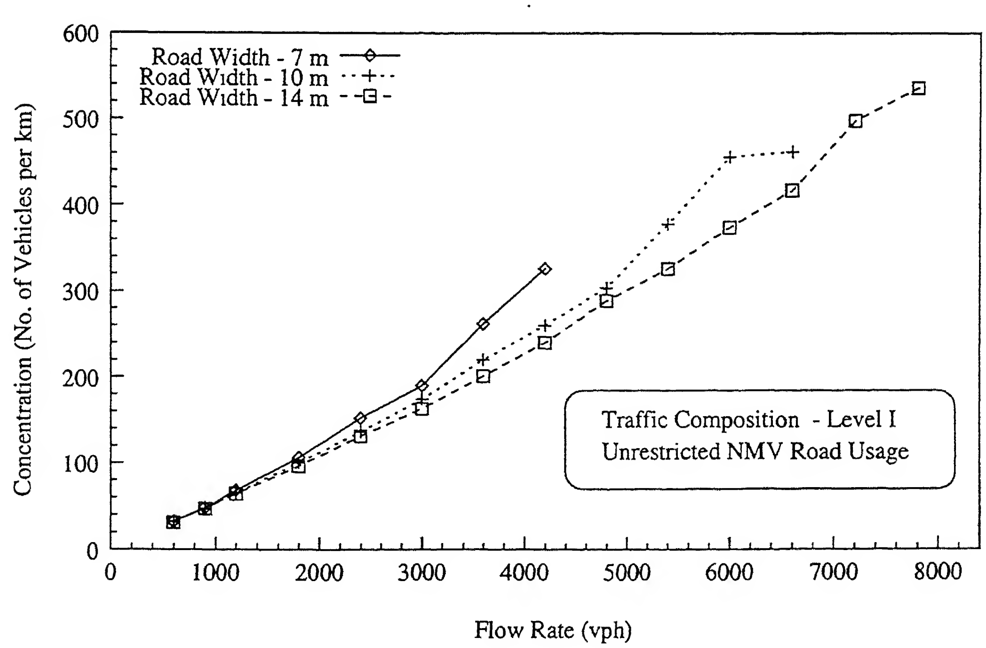


Figure 8.34: Density Flow Relationships for Different Road Widths

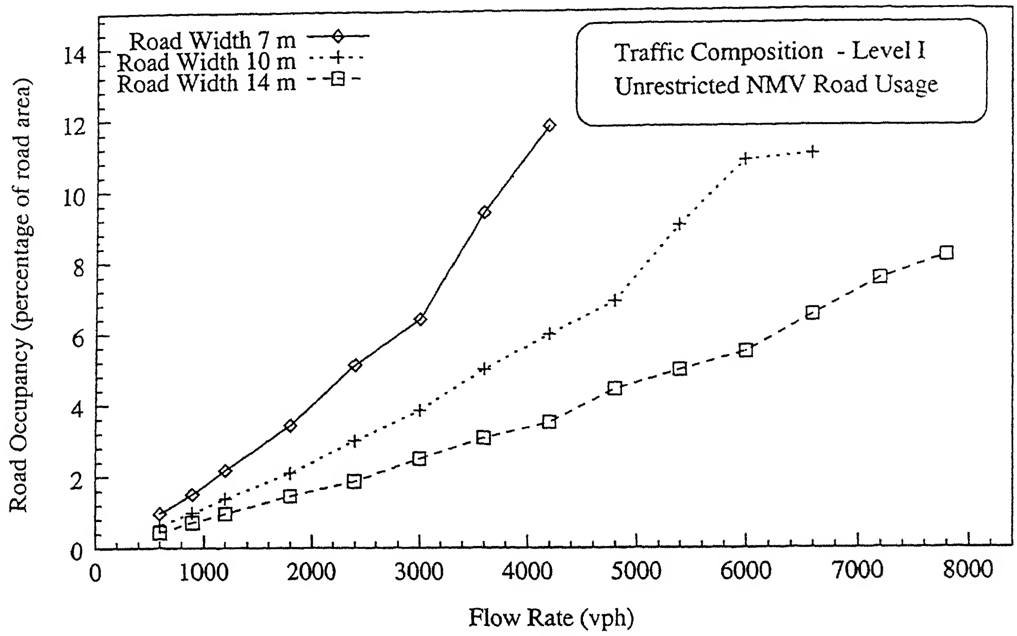


Figure 8.35: Road Occupancy Flow Relationships for Different Road Widths

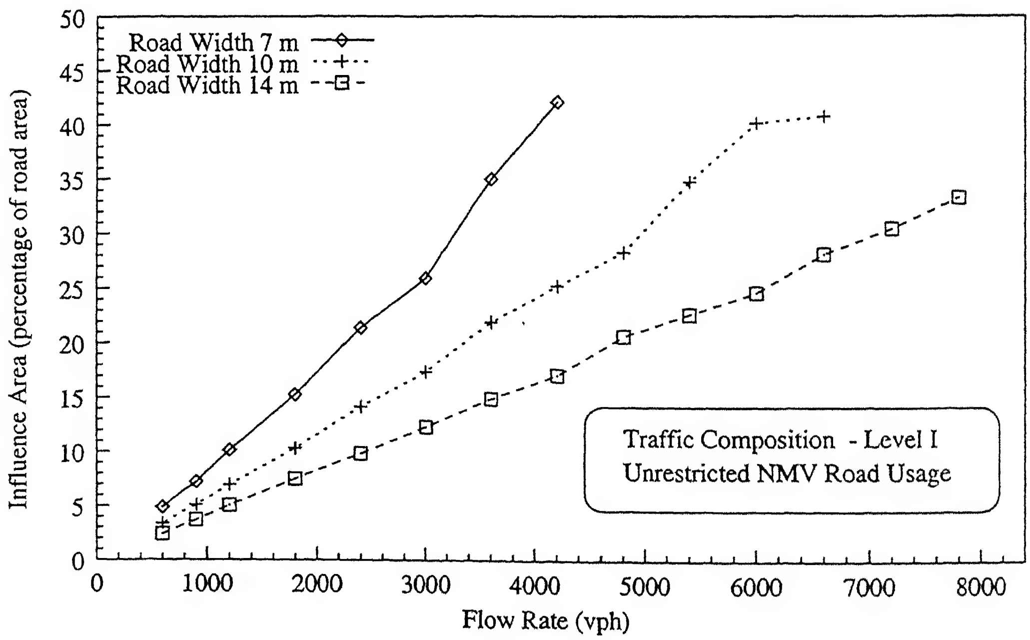


Figure 8.36: Influence Area Flow Relationships for Different Road Widths

8.8 SUMMARY

The study aims to perform sensitivity analysis of various road and traffic characteristics by conducting series of simulation runs. Initially a two lane (7m) wide level tangent road section (Road - I- benchmark road) is selected for simulation runs. To test the sensitivity of road width, two other roads of 10 m width (Road II) and 14 m width (Road III), are considered for simulation runs. The benchmark road and other two roads have unrestricted use by all non-motorised vehicles. To study the effect of restricting the road usage (segregation) of non-motorised vehicles, simulation experiments are also planned on 7 metre wide road where the non-motorised vehicle are restricted only to one lane (3.5 m width) adjacent to the road kerb.

Based on the observed traffic composition in Kanpur, a benchmark traffic composition level I (65 percent non-motorised vehicles and 35 percent motorised vehicles) is selected for simulation runs for all the three identified roads. To study the effect of traffic compositions, two more compositions (level II and III) are specified. Level II composition has equal share of motorised and non-motorised vehicles while level III composition has domination of motorised vehicles (motorised vehicles 65 percent, and non-motorised vehicles are 35 percent).

Road stretch of 500 metre length with additional warming up zone of 300 metre length is adopted in this study for simulation experiments. Simulation runs are planned at increasing flow levels till flow approaches unstable state. Six series of simulation runs are planned and each series has 8-10 flow levels. It is planned to simulate 1600 vehicles for each run. To eliminate the effect of transient state, the statistics of first one hundred vehicles are ignored.

Performance measures considered for analysis at each simulation run are:- journey speed distribution and acceleration noise of different vehicle types; road concentration (number of vehicles in the road section, road occupancy and influence area expressed as proportion of road area); and overtaking/passing maneuvers executed by different combinations of overtaking and overtaken vehicle types.

The benchmark road with unrestricted road usage for non-motorised vehicles is simulated for traffic composition of level I. Starting with a flow level of 600 vph, simulation runs are made at flow levels of 900, 1200, 1800, 2400, 3000, 3600, 4200, and 4800 vph.

To estimate the flow level that results in unstable flow condition, the simulation results for high flow levels are studied along time at 100 second intervals. By studying variation of mean journey speed with time for flow levels of 4200 and 4800 vph, it is observed that mean journey speed reduces with time, indicating that flow in unstable state. The results show that at flow level of 4800 vph, the road occupancy is increasing with time. It is also observed

that number of vehicles leaving the road stretch at different times are almost identical for flow levels of 4200 and 4800 vph. This demonstrates that the flow is in an unstable state with concentration increasing over time. The capacity of this road is estimated as 4200 vph.

The journey speed-flow relationships for different vehicle types are studied. Journey speeds reduce with flow and the level of speed reduction depends upon the vehicle type. For faster vehicles like cars, the acceleration noise is very high and it increases with flow level for all vehicle types. Road concentration is observed at every 100 second interval and mean concentration increases almost linearly with flow level. It is also observed that road occupancy increases at a certain rate upto 1800 vph and beyond this flow the rate of increase is higher.

The level of service (LOS) is a composite of several operating characteristics that are supposed to measure the quality of service as perceived by the user at different flow levels. The operating characteristics considered to define the LOS are: journey speed of cars and motorised two wheelers; concentration; and road occupancy. Based on the simulation results of benchmark road (Road - I) and traffic composition (Level - I) the levels of service are classified into the four groups (LOS I, II, III, and IV).

The movement of non-motorised vehicles is restricted to only one lane (3.5 m) adjacent to the road kerb. To study the impact of restricting road usage, comparisons have been made with performance measures of benchmark road with unrestricted non-motorised vehicles road usage. To study the sensitivity of traffic composition, the simulation runs for two other levels (level II and level III) are made and compared with results of traffic composition level I on benchmark road. Simulation experiments are made for three different road widths of 7, 10 and 14 metre. Traffic composition for all the three cases is of level I with unrestricted road usage of non-motorised vehicles.

Mathematical relationships have also been established for various performance measures. Second order polynomials are fitted to relate the performance measures with flow levels.

The study of the simulation results during sensitivity analysis clearly demonstrates the capability of simulation model to simulate traffic over different road widths, traffic compositions, and traffic operating conditions.

Chapter 9

SUMMARY AND CONCLUSIONS

9.1 SUMMARY

9.1.1 Introduction

India is witnessing rapid urbanisation due to population growth and migration to urban areas. The urban-rural population ratio which was 1:9 in 1901 and 1:4 in 1991, is expected to be about 1:3 by the turn of century. With changing urbanisation patterns along with socio-economic growth, there has also been tremendous increase in the transport demand in urban areas.

Study of traffic flow process involves analysis of the characteristics of individual vehicles in the traffic stream, as well as theoretical and empirical relationships that exist as a result of interactions among the various components. The flow of heterogeneous traffic on urban roads is highly complex and the existing analytical models cannot be used to predict the flow behaviour. Most of the available simulation models are developed to simulate the flow of homogeneous motorised vehicles. Some models have also been developed to simulate the heterogeneous traffic on rural highways. Very limited research has been attempted for simulating heterogeneous traffic on urban corridors. The available models with reference to simulation of urban heterogeneous traffic have limitations with reference to lane discipline, overtaking/yielding behaviour (meandering of narrow motorised and non-motorised vehicles), calibration and validation of models based on the observed flow process etc.

Considering the limitations of existing simulation models and need of developing new tool to justify the alternative urban traffic operational policies and measures, a model has been developed to simulate and animate the flow of urban heterogeneous traffic.

Objectives of the study are:

- Study the characteristics of road and vehicle interactions associated with the flow of

heterogeneous traffic on urban roads.

- Formulate a simulation model system for the traffic flow process on urban roads.
- Develop a model for animating the flow of simulated traffic. This graphic display may provide an insight into the working of the simulation model and also help to judge the validity of simulation flow process.
- Calibrate the parameters and decision thresholds of various sub-models of the simulation process. This calibration may be attempted by actual field observations and also through simulation experiments.
- Validation to judge the correctness of the model and the various sub-models. Validation process may be attempted through different measures of effectiveness that describe the flow. Comparisons are to be made between the observed and simulated data.
- Sensitivity analysis of various road and traffic characteristics, like road width, operating strategies, traffic composition and flow levels. This may help to define performance characteristics for various levels of service.

9.1.2 Modelling of Mixed Traffic Flow on Urban Roads

Complexities of Heterogeneous Traffic

Traffic on urban arterials in India are highly heterogeneous due to mix of different types of motorised and non-motorised vehicles. There is no definite lane pattern and road occupancy depends upon available free road space, lateral space required by vehicles on both sides and vehicle dimensions. In a constrained flow situation, one vehicle can constrain more than one vehicle and a vehicle may follow more than one vehicle at a time. Vehicles try to maximize road usage by a complex set of actions in which it is difficult to distinguish between passing, accelerative/flying overtaking or some combination of these.

Vehicle Classification for Heterogeneous Traffic

In heterogeneous traffic, vehicles have wide variation in dimensions, operating speed, acceleration/deceleration capability, power-mass ratio etc. Study indicates that about 20 vehicle types use the same roadway. These vehicles vary from fast moving car to slow moving push cart, and are present in different proportions. Some of the vehicles like cars, jeeps etc. though have some variations in their characteristics, but generally observe same type of flow logic on urban roads. Same way trucks, buses and other heavy vehicles follow similar type of flow logic. Therefore, different types of vehicles are aggregated into eight groups depending upon close resemblance in terms of physical and operational characteristics.

Road Submodel

To realistically represent the road system for mixed traffic, the road is represented by a grid pattern. This representation has the capability to quantify lateral displacement by a vehicle and also facilitates modelling various traffic interactions and their action patterns. A grid of one metre square is adopted and upto four vehicles can share this area. The model has the flexibility of changing grid size and vehicle occupancy. The effect of the vertical gradient is also considered for calculating acceleration and deceleration capability of the vehicle. Each grid element have various attributes which are both static and dynamic in nature. Static attributes constitute locational characteristics, road and traffic characteristics etc., while dynamic attributes include grid occupancy, vehicle pointers etc.

Vehicle Data Structure

Vehicle is defined as an object, consisting of static and dynamic variables. Static variables are input to the simulation model and are generated from stochastic distributions. Dynamic variables change with time and their values depend upon logical decisions taken by the vehicle. Dynamic variables describe the position, motion attributes and flow status at different times.

Traffic Generation Submodel

Aim of this model is to generate the traffic input for the simulation model and includes all parameters of the vehicle. These parameters may be directly observed from the field data or generated using specific distribution. Two different models have been proposed for traffic generation. The first model directly uses field data for traffic generation while the second model attempts to generate generalised traffic in which the attributes are randomised.

Scanning Techniques

Traffic simulation process moves the vehicles over the road and update the vehicle characteristics like lateral and longitudinal positions, speed, type of flow status - constrained, free, overtaking, yielding etc. at different times. Traffic flow process requires continuous scanning along time and road space in order to predict the position and other vehicle characteristics at different times. As continuous scanning of time and road space is not feasible in digital simulation, so time and road space are discretized. The road space is divided into grids of width Δx and length Δy.

The set of probable events that can occur is large and occur at close time intervals. In

such a situation periodic scanning is easy to formulate and is adopted in this study. Periodic scanning technique has extra advantage of compatibility with physical representation of computer model, which has been used along with vehicle pointer referencing system. Vehicle attributes are stored at specified locations and are accessed through pointers by passing the addresses of these storage locations.

Traffic Interaction Model

This model involves the study of various interactions among the vehicles and the operations related to different types of interactions. A vehicle moving on the road section may be free flowing, following, yielding, overtaking/passing at different time intervals. These types of flow logics involve changes in speed, lateral and longitudinal movement along the road. In the dynamic traffic simulation system, the decision making for these type of flow logics needs to be realistically modelled. The model has identified different types of flow logics. For each flow logic the strategy for decision making is evolved. For a particular decision, the operations to be performed like speed change, lane change etc. are determined and the flow system is updated. At any instant of time the vehicle may be operating in one of the identified flow logics.

Flow Logic of Vehicles

Broad categories of flow status for vehicles are free flowing; constrained flowing; and overtaking and yielding. For convenience in micro-level analysis, various movement types in each flow status are termed as 'mode'. Relationships are established with regard to longitudinal spacing (head length, tail length), inter-vehicular lateral spacing, lateral spacing from fixed objects, and search area.

Longitudinal Spacing

When a vehicle is following, it maintains a certain spacing with respect to the front vehicle. This spacing depends upon the speed and length of the vehicle and a certain minimum time headway. A vehicle will maintain this minimum spacing with reference to the vehicle in rear. This spacing is designated as tail length of the vehicle. As no vehicle can come within this length, tail length can be expressed as longitudinal spacing from the front of the current vehicle to the front of the vehicle behind. The distance traveled by following vehicle in reducing its speed from its own speed to the speed of vehicle infront is designated as head length of the vehicle.

Inter-Vehicular Lateral Space

Vehicles moving in a parallel stream, try to maintain adequate lateral space from each other in order to avoid side swipe. Inter-vehicular lateral space maintained by a vehicle is assumed as a function of minimum and maximum value of required lateral spacings, current speed, and minimum and maximum operating speeds of the vehicle.

Lateral Spacing from Fixed Objects

A vehicle attempts to maintain safe lateral clearance from the physical barriers such as median and road kerb etc. in order to attain safe speed and also to avoid collision. It is assumed that safe lateral spacing from the physical barrier is a function of vehicles speed.

Search Area

For decision making, area under the influence of a vehicle is to be scanned. This model specifies a certain zone to be scanned and six types of search zones are identified. Each search area has a certain length in the longitudinal direction and a certain width. Three of these areas are in the front direction and three in the rear of the vehicle. In the present study, dynamic search area as a function of current and interacting vehicle characteristics is considered.

Strategy for Decision Making of Flow Logics

The overall strategy of the traffic interaction model for the vehicle operates as follows:

- Check the status of the vehicle. Depending upon the status of the vehicle, identify the flow logic.
- Check positioning of the vehicle with reference to physical boundaries. Decision depending upon status variables may be modified, if required.
- A certain area on all sides of the vehicle is searched and the status of the vehicles in those areas are identified. The area search in lateral and longitudinal directions be consistent with the various flow logics of the vehicles.
- Do sorting of the vehicles in the search area, and select the interacting vehicles. Obtain attributes required for describing selected traffic flow operation. Attributes are calculated by studying various conditions between current vehicle and interacting vehicles.
- Update the dynamic variables of the vehicle structure and assign vehicle to new position.

Individual Vehicle Movement Characteristics

The flow process being dynamic, the stream logic for a vehicle will change with time depending upon its position, speed, status with relation to other vehicles. The flow logics in this model are classified as free, constrained, overtaking/passing, and yielding flow processes.

Free Flow Process

In free flow situation, the vehicle moves at a uniform free speed of the road block. A vehicle is said to be in free flow mode in the following situations:

- Free speed of the current vehicle is less than the speed of the vehicle ahead.
- If the available space headway is more than the sum of the head length of the current vehicle and the tail length of the vehicle ahead.

Constrained Flow Process

In the constrained flow situations, car following model is used to calculate acceleration rate based on relationship with the leading vehicle. The space headway polynomials derived from the field data are also used to compute minimum space headway between two interacting vehicles. These submodels are used in following unidirectional traffic flow situations:

- Following a slower vehicle;
- Yielding to the left in order to provide space for faster vehicle to perform passing operation.

Overtaking Process

The overtaking behaviour of a vehicle is dependent on the difference between free speeds (ΔFS) of overtaking and overtaken vehicles, and available inter-vehicular lateral spacing ($IVLS$) between the two interacting vehicles at the time of decision making. The overtaking behaviour is represented by probability function. Two probability functions are formulated, one based on ΔFS and other based on inter-vehicular lateral spacing (IVLS). The probability of overtaking is the minimum of these two probabilities.

Yielding and Passing Process

Decision making involved in passing process is identical to that of overtaking process. Maximum threshold spacing for yielding decision is same as in overtaking process. The yielding behaviour of front vehicle is stochastic in nature and is also dependent on the difference between free speed of front and rear vehicles and inter-vehicular lateral spacing between the two vehicles. Two probability functions are formulated and actual yielding probability is determined from them.

9.1.3 Model for Animation of Simulated Traffic Flow

Animated display of simulated traffic is considered to be a highly desirable feature in the field of traffic simulation. Animation can be used to visualise and explain how programmes and algorithms work by displaying animated view of simulated traffic. The main objective is to develop programme that provides animated display of the simulated traffic flow and also graphic display of individual vehicle position, velocity, and acceleration along time.

Graphical model is written in C programming language by using Starbase Graphics subroutines. Model has a capability of generating road of any length and width along with required features of urban road. Vehicle color code has been selected for all the twenty vehicle types, which helps in identifying particular type of vehicle in an animated traffic. For providing realistic view of simulated vehicles geometric modelling of all the vehicle components is done. These components are assembled to give a realistic three dimensional view.

With a three dimensional viewing facility in Starbase Graphics, it is easier to visualise various traffic operations and action patterns such as meandering, overtaking/passing etc. from any observer (camera) position referring to any point in the viewing area. In this study, periodic (fixed time interval) animation is adopted, which is further divided into two types depending upon observer position and this is classified as:

- Animation of traffic flow when observer position is fixed (Static Observer Animation) and
- Animation of traffic flow when observer is moving (Flying through Animation)

Three dimensional vision of simulated traffic from any observer position helps to demonstrate complex traffic flow process. This programme displays on screen the movement of vehicles as per the simulation programme output. The programme facilitates the user in viewing the desired part of the road stretch in a desired number of windows (view_ports) for different positions of observer. Simulation clock time, road details and other related vehicle

and traffic features can also be seen. There is a facility to fix observer on a vehicle, and it gives the feel of what driver perceives when he is driving.

Developed system of graphical models help in understanding the working of the simulation model logics and to validate the programme system of the component sub-models.

9.1.4 Traffic Studies for Simulation Model

Methodology for Data Collection and Analysis

For successful development of the simulation model for heterogeneous traffic, the various phases for which data are required include: free speed study, time headway study, space headway study for constrained flow, lateral space study (overtaking/yielding manoeuvers), lateral space study from physical barriers, and calibration/validation of model.

It is planned to collect data on a major arterial of the Kanpur city. It is four lane wide with centrally raised median. On various sections of this road, traffic volume is of the order of 1600-3000 vph during peak periods. Two sections on the road are identified for data recordings. Free speed of motorised vehicles are recorded by Radar speedometer located at three different locations. Recording was done for 16 hours on two days. Video recording of traffic flow was done for a seven hour duration, which covered both peak and off peak periods with flow varying between 1600-3000 vph in each direction. In all data for about 25000 vehicles were recorded.

For traffic flow studies, the relevant information is extracted from the video recordings. Information for a vehicle relates to its longitudinal and lateral positions at a particular time. Spot speed of a vehicle can be obtained from the longitudinal positions of the vehicle at two closely spaced time intervals. It is planned to record the image size of the vehicle at appropriate times and then estimate the position of the vehicle. Due to problems in recording and extraction, the recorded vehicle image size may not be very accurate. So a detailed calibration of distance-image size relationships for different vehicle types is attempted and a second order polynomial is adopted. Two different video image processing methods are developed for spot speed and free speed calculations. For recording the inter-vehicular lateral spacing and spacing from the fixed objects, strategies for data extraction and analysis are developed.

Parameter Estimation

Time headway analysis is done for six data sets, each of one hour duration. For the observed time headways, three composite headway distributions considered are: Schuhl, Modified-

Schuhl (time headways of motorised and non-motorised vehicles are segregated), and Dawson composite headway distribution. Goodness of fit tested by K-S test confirm that Schuhl and Modified-Schuhl distributions describe the observed time headways. For the observed free speed data, Normal distributions were fitted for different vehicles type.

Recorded video data was analysed to extract the following information with respect to interacting vehicles.

- Lateral spacing between the overtaking and overtaken vehicles when both are parallel.
- Speed of overtaking vehicle when parallel to overtaken vehicle.
- Speed of the overtaken vehicle.

It is observed that each vehicle maintains a certain minimum clearance to avoid lateral collision. However, as the speed of the vehicle increases, it has a tendency to maintain higher lateral spacing. The recorded data set is used to estimate the minimum, maximum, and distribution of lateral clearances for different vehicle types.

The probability of overtaking and yielding in a situation depends upon the available lateral space. The probability of overtaking varies linearly with the available lateral space subject to constraint of minimum and maximum lateral space of the relevant vehicle group.

Lateral space study data for different combinations is analysed to estimate the speed of overtaking vehicles when passing by the side of vehicle being overtaken. It is observed that the overtaking vehicle speed increases with lateral spacing and also depends upon the overtaken vehicle speed. Appropriate relations are established.

Information of lateral spacing from the road side objects was extracted from video data for different types of vehicles. In all about 400 observations of this lateral spacing are analysed. To estimate the safe lateral clearance from physical barriers, two relationships are established.

Longitudinal spacing for the constrained vehicle depends upon type of interacting vehicles. Data for about 20-40 observations is extracted for each of the feasible combination. It is observed that longitudinal spacing increases with the speed of the vehicle ahead and also the speed of the rear vehicle. While establishing the relationship, it is considered that longitudinal spacing in constrained situation depends upon the speed of the front vehicle and the difference in the speed of the front and rear vehicles.

The overtaking/yielding behaviour of vehicle depends on the difference between free speed of overtaking and overtaken vehicles (ΔFS) and inter-vehicular lateral spacing ($IVLS$) between the two vehicles. For different combinations of overtaking and overtaken vehicle

groups, minimum and maximum values of inter-vehicular lateral spacing are observed during lateral space study. Probabilistic relations are established for overtaking/yielding decisions.

9.1.5 Calibration of Simulation Model

The validation process, adopted in this study, consists of the following three broad components:

- Validity of programme logics through animation of simulated traffic
- Calibration of simulation model
- Overall model validation

The formulated traffic simulation model consists of a series of sub-models. The realistic estimate of various parameters and decision thresholds is attempted in the calibration process. The different parameters, decision thresholds and performance measures that need to be calibrated in various submodels are:

Traffic Generation Model: entry time, free speed, entry speed, lateral position at entry, power mass ratio, rolling and air resistance coefficients.

Traffic Interaction Model:

- Longitudinal space for vehicle interaction
  - Tail length
  - Head length
- Lateral space for vehicle movements
  - Inter-vehicular lateral space
  - Lateral space from physical barriers
- Search areas to study vehicle interactions
- Constrained flow logic
  - Estimation of speed of the constrained vehicle as per available longitudinal space
- Overtaking/yielding flow process
  - Decision point for flying overtaking (longitudinal space with respect to vehicle ahead)
  - Performance measures for overtaking
    - Estimation of overtaking speed

Some submodels require calibration against the observed data. It is also necessary to calibrate the values of some parameters and decision thresholds in the light of simulation results. Three sequential stages of the calibration process as adopted in this study are:

- **Stage I** - Estimation of some parameters based on analysis of direct field measurements.
- **Stage II** - Estimation of some parameters and decision thresholds based on the observations and inferences of this and other studies.
- **Stage III** - Calibration of parameters for decision process and various performance measures based on experimental simulation runs.

Calibration of traffic interaction model is done by fixing the value of parameters and decision thresholds of submodels. Minimum time headway of 1.0 second has been considered for all type of vehicles to calculated tail length. The value of maximum deceleration rate adopted is 2.0 m/sec^2.

Analysis of observed field data has estimated the parameters of minimum and maximum lateral space for different vehicle types. The calibration of adjustment factor for lateral space is done from the results of the simulation runs. The comparison of results helped in fixing the value of adjustment factor as 0.7.

Trial runs were made for different values of multiplying factor for search length and it ranging between 1.0-2.0. Finally the value of multiplying factor adopted is 2.0. Parameters of the longitudinal space submodel, overtaking and yielding submodels, estimation of overtaking speed polynomials are calibrated from field studies and results of previously conducted field studies.

When a faster vehicle catches up a slower vehicle ahead, it has to take a decision whether to perform flying overtaking or start following. Interaction distance for decision point is calibrated as twice the sum of head length and tail length.

The experimental simulation runs are made on the road for which the field observations are available. A stretch of 100 metre length is selected and traffic is simulated for two different flow levels. Comparison of the observed and simulated values of journey speeds for different vehicle types are made. Simulated values are for two different approaches:

Approach I: Car following model for constrained flow and

Approach II: Space headway polynomials for constrained flow

These comparisons indicate that approach I gives results more close to the observed values. The reason for variation in approach II may be because of limited number of data

points for which space headway polynomials were established. Approach I is finally adopted for validation and simulation experiments for sensitivity analysis.

9.1.6 Validation of Simulation Model

The overall validation of the simulation model is a test of how well the submodels have been assembled into a realistic structure of the system. The measures of effectiveness selected for validation are: journey speeds, time headways, traffic density, and number of overtakings performed. For each of the measure selected for validation, the frequency distribution of the observed and simulated values are compared. For comparison of observed and simulated values, different vehicle types are divided into six groups. These groups are cars, motorised three wheelers (Tempo/Auto Rickshaw), heavy motor and light commercial vehicles, motorised two wheelers, bicycles, and cycle rickshaws.

Concentration is normally expressed in terms of number of vehicles per km per lane. For the heterogeneous traffic mix, the vehicles have wide variation in dimensions and other characteristics, and there is no specific lane discipline. A better approach adopted is with reference to the proportion of road space occupied by the vehicles. Concept of proportion of road space influenced by traffic is also adopted for analysing sensitivity experiments. Comparison of the observed and simulated road space occupancy or influence area is made through:

- Variation of road occupancy over a period, the observations being made at every 15 sec interval.
- Maximum road space or influence area at any instant during the simulation run. This measure shows the effect of platooning.
- Mean and standard deviation of the road occupancy.

Simulation runs are made at flow level different from one used for calibration. This helps to test the capability of model under different conditions. Simulation run is made for an hourly volume of 2332 vph observed during the peak period.

Estimated values of mean and standard deviation indicate that simulated and observed journey speeds are very close, the difference being within ± 0.4 m/sec (about 1.5 kmph). Only in one case of heavy vehicles (LCV & HCV), the difference is slightly higher. The standard deviations of observed and simulated journey speeds are very close, being within ± 0.3 m/sec (1 kmph). The nature of frequency distributions are quite identical for all cases.

The observed and simulated values of mean and standard deviation of inter-vehicle group time headways at exit are quite close for most of the cases. Only for cycle rickshaw, the difference between the standard deviation of observed and simulated traffic is 1.31 seconds.

The variation of road occupancy over time is studied both for simulated and observed data. Variation of simulated values over time is generally identical to the observed values. The mean road occupancy for the observed data is 4.99 percent of the total road area and 5.23 percent for the simulated values. This difference is marginal due to wide dispersion of the values. The simulated and observed number of overtakings are quite comparable for most of the cases. These comparisons demonstrate the capability of the simulation model to realistically represent the complex heterogeneous traffic flow.

9.1.7 Sensitivity Analysis

Design of Simulation Experiments

The study aims to perform sensitivity analysis of various road and traffic characteristics by conducting series of simulation runs. Initially a two lane (7m) wide level tangent road section (Road - I- benchmark road) is selected for simulation runs. To test the sensitivity of road width, two other roads of 10 m width (Road II) and 14 m width (Road III), are considered for simulation runs. The benchmark road and other two roads have unrestricted use by all non-motorised vehicles. To study the effect of restricting the road usage (segregation) of non-motorised vehicles, simulation experiments are also planned on 7 metre wide road where the non-motorised vehicle are restricted only to one lane (3.5 m width) adjacent to the road kerb.

Based on the observed traffic composition in Kanpur, a benchmark traffic composition level I (65 percent non-motorised vehicles and 35 percent motorised vehicles) is selected for simulation runs for all the three identified roads. To study the effect of traffic compositions, two more compositions (level II and III) are specified. Level II composition has equal share of motorised and non-motorised vehicles while level III composition has domination of motorised vehicles (motorised vehicles 65 percent, and non-motorised vehicles are 35 percent).

Road stretch of 500 metre length with additional warming up zone of 300 metre length is adopted in this study for simulation experiments. Simulation runs are planned at increasing flow levels till flow approaches unstable state. Six series of simulation runs are planned and each series has 8-10 flow levels. It is planned to simulate 1600 vehicles for each run. To eliminate the effect of transient state, the statistics of first one hundred vehicles are ignored.

Performance measures considered for analysis at each simulation run are:- journey speed

distribution and acceleration noise of different vehicle types; road concentration (number of vehicles in the road section, road occupancy and influence area expressed as proportion of road area); and overtaking/passing manoeuvers executed by different combinations of overtaking and overtaken vehicle types.

Analysis of Results for Bench Mark Road (Road - I) and Traffic Composition of Level I

The benchmark road with unrestricted road usage for non-motorised vehicles is simulated for traffic composition of level I. Starting with a flow level of 600 vph, simulation runs are made at flow levels of 900, 1200, 1800, 2400, 3000, 3600, 4200, and 4800 vph.

To estimate the flow level that results in unstable flow condition, the simulation results for high flow levels are studied along time at 100 second intervals. By studying variation of mean journey speed with time for flow levels of 4200 and 4800 vph, it is observed that mean journey speed reduces with time, indicating that flow in unstable state. The results show that at flow level of 4800 vph, the road occupancy is increasing with time. It is also observed that number of vehicles leaving the road stretch at different times are almost identical for flow levels of 4200 and 4800 vph. This demonstrates that the flow is in an unstable state with concentration increasing over time. The capacity of this road is estimated as 4200 vph.

The journey speed-flow relationships for different vehicle types are studied. Journey speeds reduce with flow and the level of speed reduction depends upon the vehicle type. Vehicles of high free speed, i.e., cars and motorised two wheelers have high speed reductions even at low flow levels and journey speed of non-motorised vehicles have very minor variations with flow level. For faster vehicles like cars, the acceleration noise is very high and it increases with flow level for all vehicle types. Road concentration is observed at every 100 second interval and mean concentration increases almost linearly with flow level. It is also observed that road occupancy increases at a certain rate upto 1800 vph and beyond this flow the rate of increase is higher. The mean journey speed of all vehicles varies almost linearly with concentration. The variations of overtakings with flow are studied for some combinations of vehicle groups.

Level of Service

The level of service (LOS) is a composite of several operating characteristics that are supposed to measure the quality of service as perceived by the user at different flow levels. The operating characteristics considered to define the LOS are: journey speed of cars and motorised two wheelers; concentration; and road occupancy. Based on the simulation results

- The journey speeds of motorised vehicles for traffic composition of level II and III are higher than those for traffic composition level I upto flow level of 3000 vph. The difference between the journey speeds for traffic composition level II and III are very marginal.
- The concentration for level II and III are less than that of level I. However, the percentage road occupancy and percentage influence area are highest for level III traffic composition.
- Number of overtakings performed by motorised vehicles are higher for traffic composition level II and III than level I due to high proportion of motorised vehicles. The total number of overtakings performed by all vehicles are least for traffic composition of level III.
- The estimated maximum service flow for the four levels of service LOS I, II, III, and IV are 900, 2100, 3100, and 3600 vph for traffic composition of level II, while the corresponding values for traffic composition of level III are 900, 2100, 3000, and 3500 vph (Table 8.9 of Chapter 8).

Analysis of Simulation Results for Different Road Widths

Simulation experiments are made for three different road widths of 7, 10 and 14 metre. Traffic composition for all the three cases is of level I with unrestricted road usage of non-motorised vehicles. The study of performance measures demonstrates the following observations:

- For the 7 m wide road, unstable state is observed at flow level of 4200 vph. For the 10 metre wide road, flow is unstable beyond level of 5400 vph, while for 14 metre width, the road capacity is 6600 vph (Table 8.9 of Chapter 8).
- At low flow levels, vehicles move at speeds close to their free speed in all the three road widths. At high flow levels, the mean journey speed for 14 metre road is about 4 m/sec (15 kmph) higher than that of 7 metre road.
- The journey speeds of non-motorised vehicles are also high for wider roads, but this difference is significant only at very high flow levels.
- The traffic concentration, road occupancy, and influence area are less for wider roads due to increased journey speeds.
- It is estimated that the maximum service flow for unstable state are 5400 and 6600 vph for roads of 10 and 14 metre width respectively. For the four levels of service, the estimated maximum service flow are 900, 2700, 4500, and 5400 vph for 10 metre wide road, while the corresponding values for 14 metre wide road are 1200, 3600, 5800, and 6600 vph (Table 8.9 of Chapter 8).

The study of the above simulation results clearly demonstrates the capability of simulation model to simulate traffic over different road widths, traffic compositions, and traffic operating conditions.

9.2 CONCLUSIONS

On the basis of this study, the following conclusions can be drawn:

- Traffic simulation system has a series of sub-models which have been assembled into a realistic structure of the system. The model is capable of simulating different types of non-motorised and motorised vehicles.
- Concept for optimisation of road space usage has been modelled and it helps in describing complex urban heterogeneous traffic flow process.
- The grid system for the representation of the roadway, pointer reference system for vehicle and the scanning of the search area adopted in the model, have helped to realistically model the complex movement of heterogeneous traffic.
- Traffic interaction model involves series of flow logics associated with free flow, constrained flow, overtaking and yielding process. These formulated flow logics are quite comprehensive and some are also probabilistic in nature.
- Animation of the simulated traffic flow has helped to formulate realistic flow logics.
- Animation also provides user an insight into the working of simulation model.
- Data collected for field studies have been analysed to establish the relationships and estimate the parameters, decision thresholds for the following:
  - Free Speed Study
  - Time Headway Study
  - Space Headway Study for Constrained Flow
  - Lateral Space Study (Overtaking/Yielding Maneuvers)
  - Lateral Space Study for Vehicles from Physical Barriers, i.e., Median, Pedestrian Way etc.

  The established relationships have been incorporated in the various sub-models of the traffic simulation system.
- Three stage calibration process has helped to calibrate various parameters and decision thresholds of various component sub-models.

- The overall validation of the simulation model has been successfully attempted by using different measures of effectiveness, which represent the output of whole system.

- The experimental design for the simulation run has been formulated and strategies of simulation length and starting conditions have been established. The concept of "warm up" section has been highly appropriate for the traffic system.

- The performance of the simulation model with reference to different road and traffic characteristics has been studied by series of simulation runs.

- Analysis of simulation results for the benchmark road have helped to define for different levels of service (LOS I, II, III, and IV) and the associated performance measures. These levels of service could be used to lay down the design standards. Analysis of different simulation experiments have helped to estimate the maximum service flow for the four defined levels of service.

- The developed simulation model can be used to estimate traffic interactions under different traffic volumes, composition levels and geometric standards and thus to design the road geometrics and traffic management measures under the desired level of service. It can also be helpful in future planning and design of urban road facilities.

9.3 SUGGESTIONS FOR FURTHER RESEARCH

The results of the study are highly encouraging and desire refinements and extensions of the model in the analysis of complex heterogeneous traffic flow. Based on the results of this study, the following suggestions are made for future work:

- Model the flow of bi-directional traffic.

- Model the flow of heterogeneous traffic through different types of signalised and unsignalise intersections. This will facilitate to simulate heterogeneous traffic on urban corridor and design the signal timings.

- Model the flow through horizontal and vertical curves and incorporate impact of sight distance and road roughness.

- Field studies on number of different types of road for fine tuning the calibration of model parameters under various conditions.

- Validate the model for series of urban corridors of different geometrics, traffic compositions and flow levels.

- Perform simulation experiments to study the sensitivity of the various road and traffic characteristics.

- Detailed statistical analysis be attempted to establish the relationships for performance measures to estimate the passenger car units (PCU) for different vehicles in terms of road geometrics, traffic flow, and composition.

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Appendix A

COMPUTER ALGORITHMS

A.1 ALGORITHM FOR MAIN TRAFFIC SIMULATION PROGRAMME

Step 0. Start.

Step 1. Read following traffic, road, and vehicle attributes:

- Traffic data.
- Road data.
- Distributions of lateral space, overtaking speed and space headway.
- Mean, standard deviation, minimum and maximum values of inter-vehicular lateral spacings for different groups.
- Air and rolling resistance coefficients.
- Normal distribution parameters of free speed for different vehicle types.
- Cumulative power mass ratio distributions of different vehicle types.
- Other parameters used in traffic generation.

Step 2. Generate road system for unidirectional flow with centrally raised median.

Step 3. Generate traffic as directly observed from the field or randomised traffic.

Step 4. Initialise time = t_start, road_system_empty_flag = FALSE.

Step 5. Move and assign the vehicles present at given time t on the road system according to the traffic flow logic. Possible decisions which may be taken by a vehicle are given here under:

- Entry in the simulated road section.

- Yielding
- Right overtaking
- Left overtaking
- Forward movement
  - Free flowing
  - Constrained flowing

Step 6. a Initialise, assign_flag = FALSE.

Step 6. b If (road traffic queue is not NULL and time of vehicle on top of the queue is less than current time) then
Check for space available for vehicle to enter in the road system;
else
go to Step 7.

Step 6. c If (space is available for vehicle to enter in the road system) then assign vehicle to the road system and assign_flag = TRUE.

Step 6. d If (assign_flag==TRUE) then go to Step 6. a.

Step 7. Analyse for overtaking, yielding, and other operations performed during current simulation time.

Step 8. Store vehicles information for statistical analysis.

Step 9. Print vehicles information for animation program and other analysis requirement.

Step 10. Check for the road system occupancy status, if the road system is empty then road_system_empty_flag=FALSE
else road_system_empty_flag = TRUE.

Step 11. time = time + deltat.

Step 12. If ((time < end_time) or (road_system_empty_flag == FALSE)) then go to Step 5.

Step 13. Calculate statistics of traffic flow parameters. Statistics includes the following:

- Percentage of the road space occupied by the vehicles.
- Journey speed distributions.
- Spot speed distributions.
- Time headway distributions.
- Overtaking distributions, it includes passing, flying and accelerative overtaking.

- Concentration
- Flow status
- acceleration noise

Step 14. Stop.

A.2 MACRO ALGORITHM FOR LT_MOVE FUNCTION

Step 0. Start.

Step 1. if(proc_time > stip_proc_time) then
{

- proc_time = 0.0; and
- change the status of overtaking and yielding flags.

where proc_time	=	present time of process for which left move function is called
stip_proc_time	=	stipulated process time

}

Step 2. Call left_move function.

Step 3. Get x_dist_left, y_dist, move_flag and proc_time

where x_dist_left	=	left lateral displacement
y_dist	=	longitudinal displacement
move_flag	=	movement flag

Step 4. If (move_flag = FALSE) then go to Step 8.

Step 5. Call function coord_calc, it calculates distance moved by vehicle in longitudinal direction, speed and acceleration for given value of y_dist.

Step 6. Change position of vehicle by x_dist_left and y_dist; assign vehicle attributes to the new grid elements by vehicle assign function. Vehicle assign function assigns vehicle attributes to the new grid elements and assigns check and flag boolean variables as TRUE.

Step 7. Assign previous grid positions occupied by vehicle as follows:

ro[i][j].veh[g_no]	=	NULL;
ro[i][j].check[g_no]	=	TRUE;
ro[i][j].flag[g_no]	=	FALSE;

Step 8. Stop.

A.3 MACRO ALGORITHM FOR LEFT_MOVE FUNCTION

Step 0. Start.

Step 1. If(yield_flag = TRUE) possibility of yielding, go to Step 2; else possibility of overtaking from left, go to Step 3;
where yield_flag = true for yielding and false for left overtaking.

Step 2. Check flags (Overtaking and Yielding Flags) status for yielding decision. Depending upon decision taken assign *l_flag as True or False.
where *l_flag = left movement flag.

Step 3. Check flags (Overtaking and Yielding Flags) status for overtaking decision from the left. Depending upon the decision taken assign *l_flag as True or False. As shown

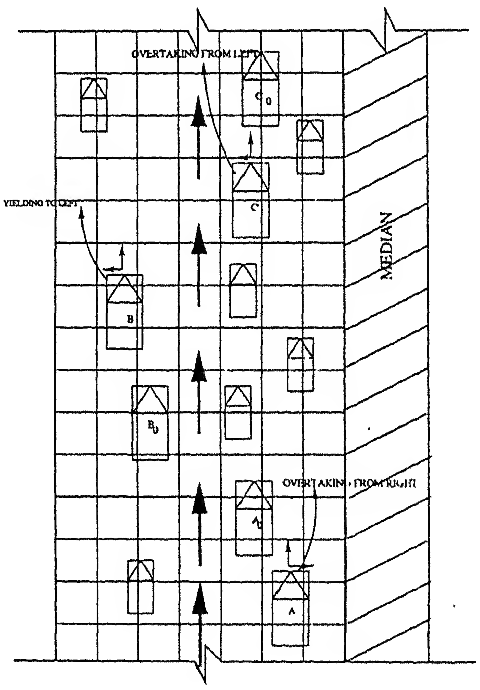

Figure A.1: Illustrating Flag Status (Right Overtaking Flag, Left Overtaking Flag and Yielding Flag) of the Vehicles by Considering Overtaking and Yielding Operations Performed by the Vehicles

in Figure A.1 vehicles A_0, B_0 and C_0 are neither performing overtaking nor yielding operations. Vehicle A is overtaking vehicle A_0 from the right direction. Therefore, right overtaking flag status of vehicle A is TRUE and rest of the decision flags are

FALSE. Similarly for vehicle B yielding flag is TRUE and rest of the decision flags are FALSE. Vehicle C left overtaking flag is TRUE and rest of the decision flags are FALSE. This description will help in understanding the decision making involved in Step 4 and Step 5 which depends upon status of the overtaking and yielding flags.

Step 4. Get following attributes:

- Corresponding group number for the current vehicle type.
- Acceleration capability at current speed.
- Lateral space required by the vehicle.
- Lateral clearance from the fixed object.

Step 5. Check vehicle positioning with reference to the left most boundary of the road. This can be accomplished in the following manner:
If((Left most x_coordinate of the current vehicle -lateral spacing (lateral spacing required from the left most boundary)) > left most coordinate of the road)
then *l_flag = TRUE; else *l_flag = FALSE; As shown in Figure A.2, vehicle A can

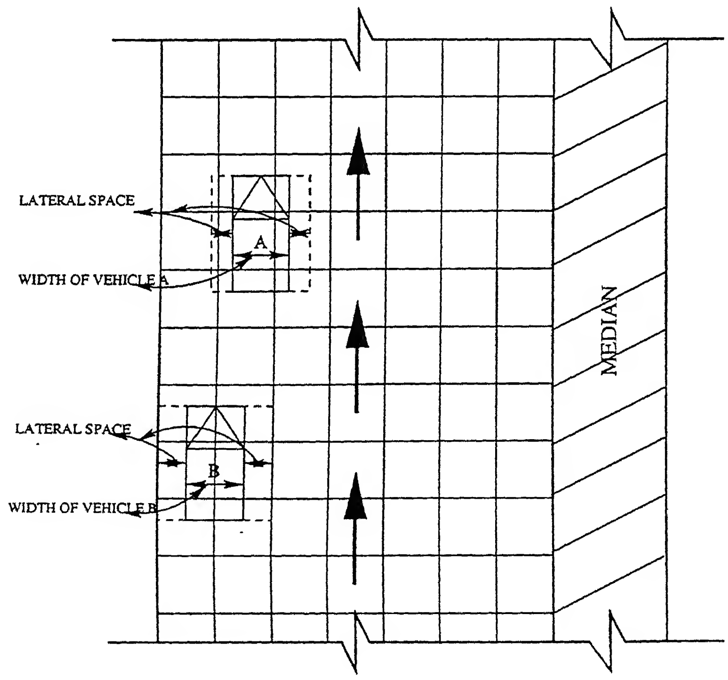

Figure A.2: Effect of Lateral Space Required by the Vehicle from Physical Barriers (Left Boundary of the Road) during Left Movement (Left Move Sub-Model)

move to the left, but it is not possible for vehicle B to shift in the left direction.

Step 6. Check vehicle position with respect to desired area and assign *l_flag as True or False. Reference can also made to Figure A.3 in which vehicle A is out of his desired area and already overtaken vehicle B from the right. Therefore, in this case above mentioned condition will be TRUE and *l_flag will be assigned as TRUE. However, vehicle C is out of his desired area but it has not overtaken slow moving vehicle D. Therefore, at the present simulation time it is not possible for vehicle C to come in his desired area. So in this case *l_flag will be assigned as FALSE.

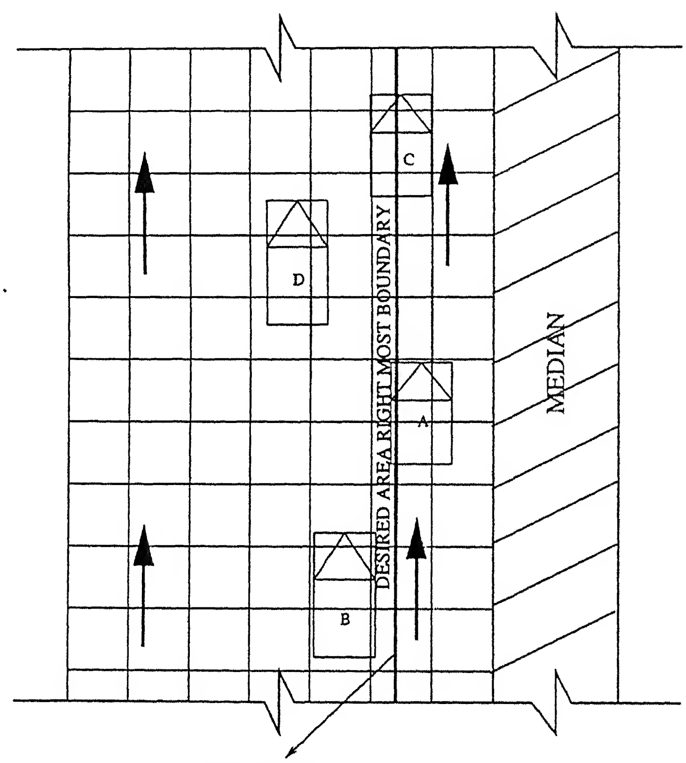

Figure A.3: Effect of Desired Space on Vehicles Left Movement (Left Move Submodel)

Step 7 if(*l_flag=TRUE) go to Step 8a else go to Step 26.

Step 8a Initialise prob_flag = TRUE.

Step 8b If(yield_flag = True and rac_flag=TRUE) go to Step 8c else go to Step 12a. Where rac_flag = rear area check flag.

Step 8c. Get rear search area of the current vehicles (Figure 3.13). Scan rear search area of the current vehicle to get vehicles, which are to be considered for yielding (Figure A.4).

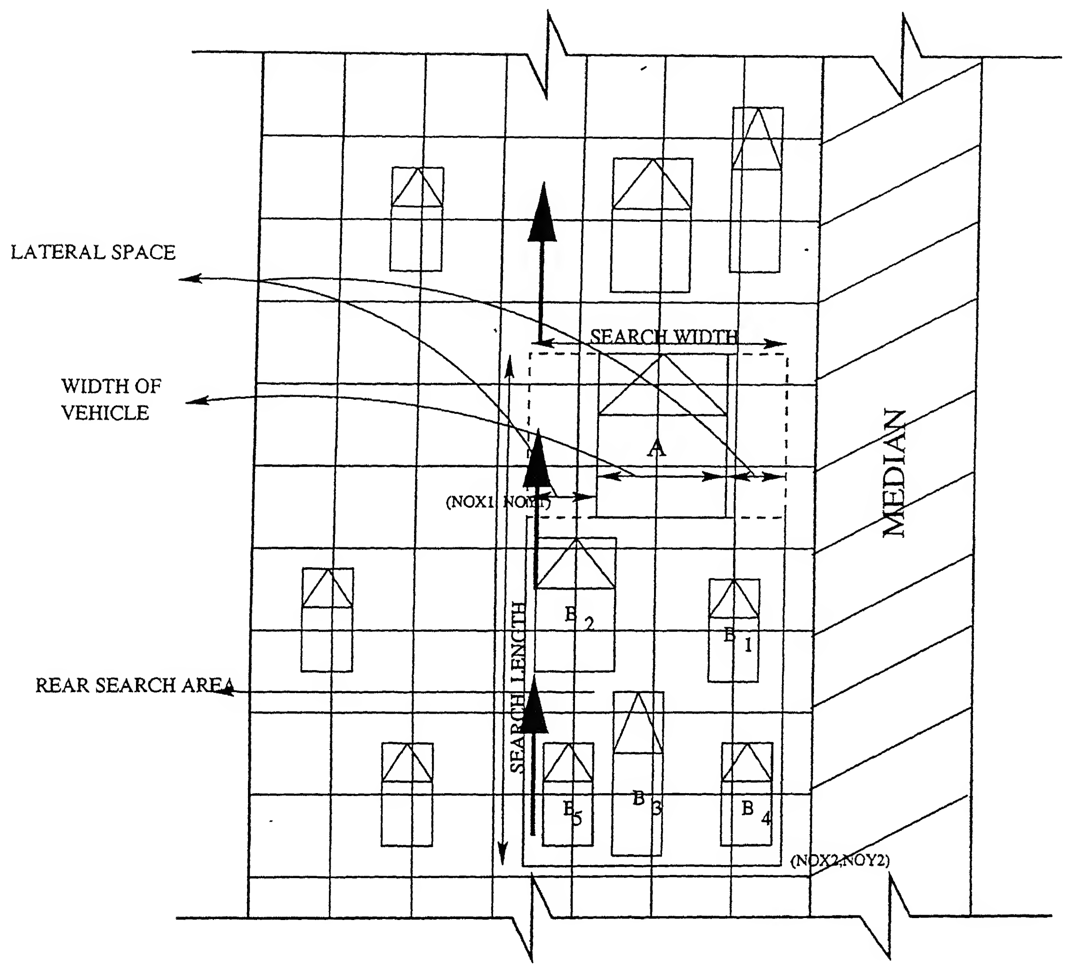

Figure A.4: Scan Vehicle Rear Search Area for Yielding Decision

Step 9. Atmost four vehicles can acquire particular grid element (Figure A.5). Store vehicles attributes into temporary storage, which are present in the rear search area. Analyse the temporary storage in the following way:

- if ((Difference in longitudinal position of the current and interacting vehicles) $\leq$ (required interaction length)) then interaction_flag = FALSE else interaction_flag = TRUE.
- Calculate probability of the yielding of current vehicle with interacting vehicles in rear by difference in free speed and inter-vehicular lateral spacing method.
- If (generated probability $\leq$ required probability) then prob_flag = TRUE else prob_flag = FALSE.

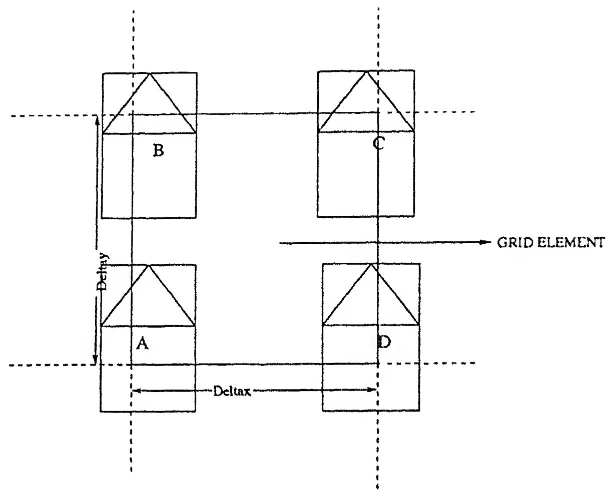

Figure A.5: Maximum Number of Vehicles which can be Accommodated in One Grid Element

Step 10a. Do sorting of the vehicles which are stored into temporary storage; it is clear from Figure A.4 vehicles which are stored into temporary storage are B_1, B_2, B_3, B_4, and B_5. Vehicle attributes which are stored are as follows: lateral and longitudinal positions, speed, group number, identity number, vehicle type, power mass ratio, spacing flag, and interaction flag. Get those vehicles which are just behind of the current vehicle without any obstruction. In this case these vehicles are B_1 and B_2. Choose those vehicles only whose interaction flag and yielding flag is TRUE. Select left most vehicle and calculate maximum lateral distance required by the current vehicle to yield.

Step 10b. Register x coordinate, group number, speed, vehicle type and identity number into temporary storage of the vehicle for which current vehicle is yielding.

Step 11. if(*l_flag = TRUE and (prob_flag = TRUE or des_flag = TRUE or left_ov_flag = TRUE))
go to Step 16a (left movement calculation is needed);
else go to Step 31.

where *l_flag	=	left movement flag;
prob_flag	=	probability flag;
des_flag	=	desired space flag; and
left_ov_flag	=	left overtaking flag.

Step 12a. Get left frontal search area and check the same (Figure 3.13).

Step 12b. Check left side area infront of the current vehicle (Figure A.6 and Figure 3.13).

Step 13. Store vehicle into temporary storage. From Figure A.6 vehicles stored into temporary storage are A_1, A_2 and A_3. Vehicle attributes which have to be stored are as

follows: lateral and longitudinal positions, longitudinal separation with current vehicle, lateral separation with current vehicle, front headway, power weight ratio, interaction flag, vehicle type, group number and identity number.

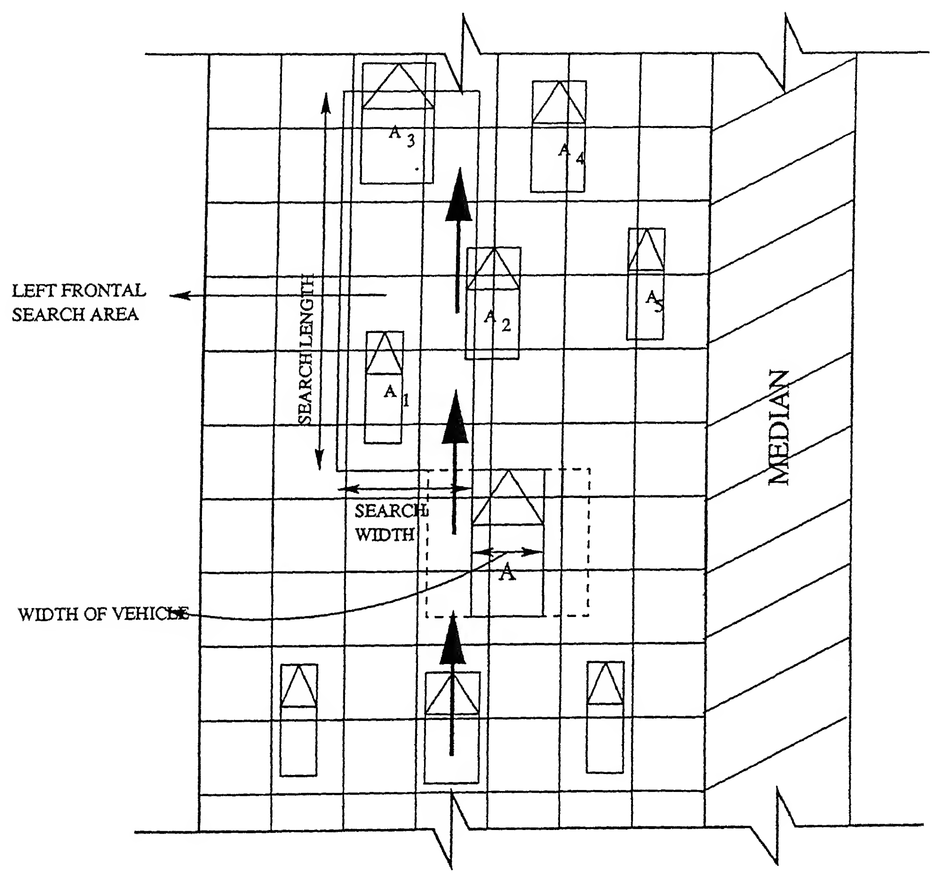

Figure A.6: Scanning Left Frontal Search Area for Calculating Possible Left Movement of the Vehicle

Step 14. Calculate left_x1 and *y_dist on the basis of vehicle stored in temporary storage. Where left_x1 = possible left lateral displacement by considering left frontal area; and y_dist = possible longitudinal displacement by considering left frontal area. Calculate check_distance, where check_distance = width of the vehicle + lateral space required on one side.

Step 15. if(left_x1 < check_distance) then go to Step 16 else go to Step 20.

Step 16. Calculate width of the strip to be checked infront of current vehicle. See Figure A.7. From Figure A.7 vehicles which are stored into temporary storage are A_1 and A_2. Stored vehicle attributes are same as left front area case.

Step 17. Store vehicle attributes into temporary storage, which are directly infront of the current vehicle and lying in the strip area.

Step 18. Analyse temporary storage; if it is required to modify *y_dist and left_x1 modify it.

Step 19. If{ left_x1 $\leq$ 0.0 } then
{ *l_flag = FALSE;
go to Step 26; }
else {
l_flag = TRUE;
go to Step 20 }

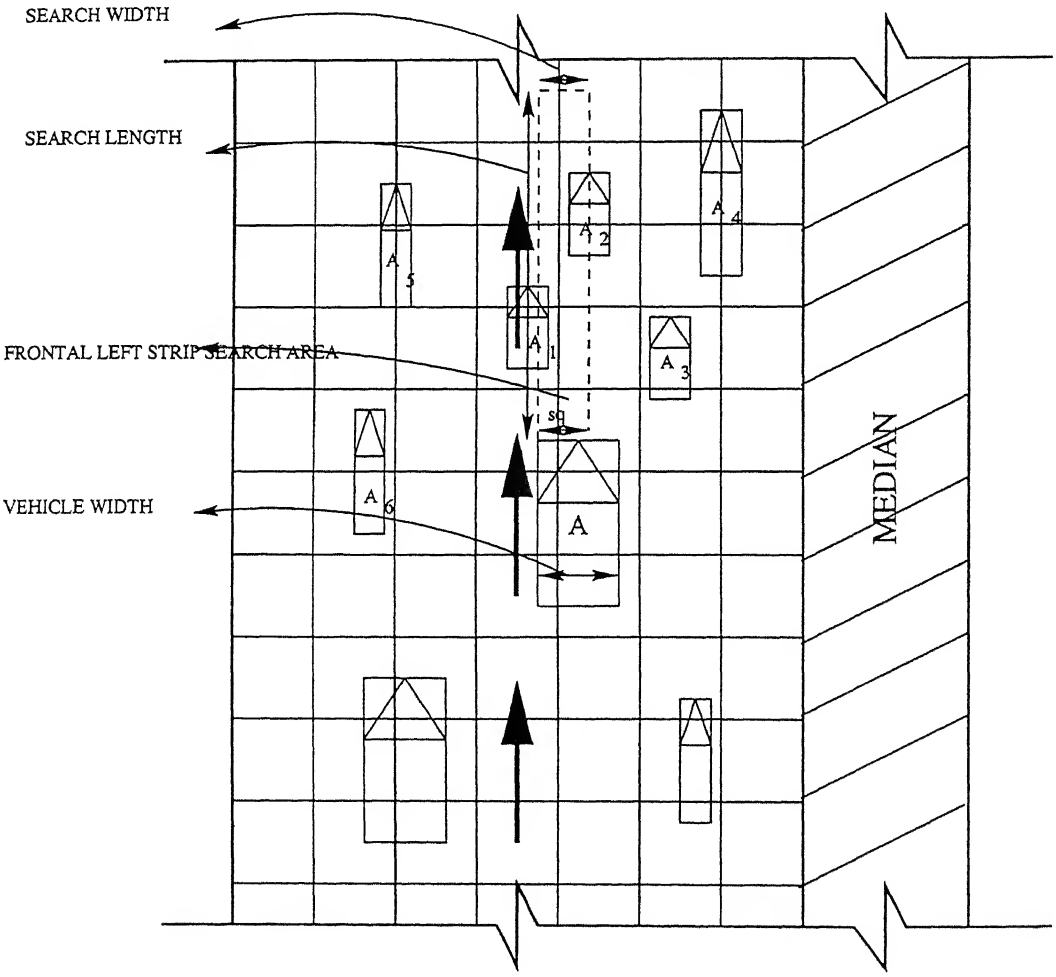

Figure A.7: Scanning Front Strip Search Area after Considering Possible Left Movement of the Vehicle by Scanning Left Frontal Search Area

Step 20. Get left rear search area (Refer to Figure 3.13) and check the same. See FigureA.8 and Figure 3.13. From Figure A.8, it is clear that vehicles which are stored into temporary storage are B_1, B_2, B_3 and B_4. Stóred vehicle attributes are same as left front area case.

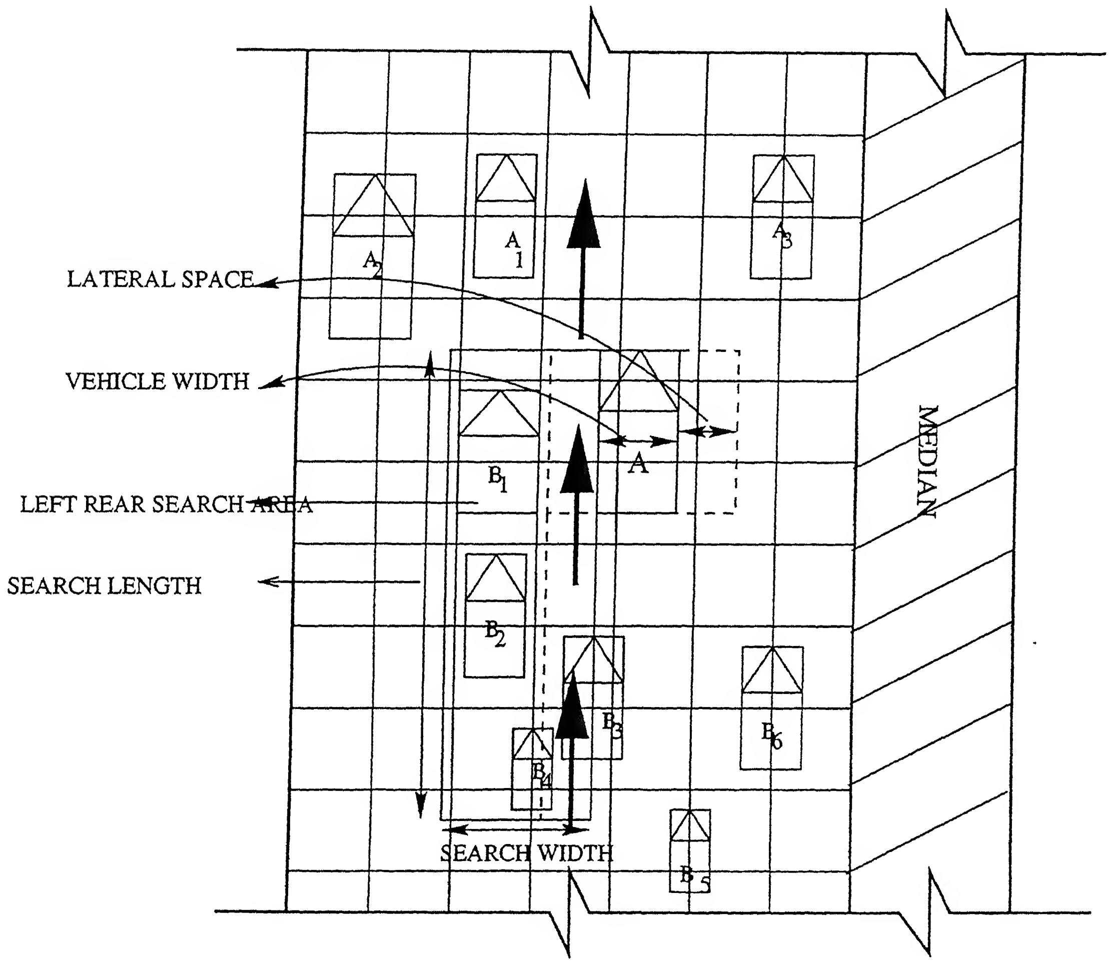

Figure A.8: Scanning Left Rear Search Area for Possible Left Movement

Step 21. Calculate left_x2 on the basis of vehicle stored in temporary storage.

Step 22. if(left_x1 $\leq$left_x2)
x_dist = left_x1
else
x_dist = left_x2
Where left_x2 = maximum possible x displacement obtained from checking left rear search area.

Step 23. Remodify *x_dist on the basis of left most boundary of road, distance from the fixed object (left side encroachment and kerb), and required yielding distance (req_x_dist).

Step 24. If (*x_dist < req_x_dist)
then modify (req_x_dist) distance required by which current vehicle has to yield in order to provide space for overtaking vehicle; req_x_dist = req_x_dist - *x_dist;
else req_x_dist = 0.0.

Step 25. If{req_x_dist==0.0} then modify flag status.

Step 26. Stop.

A.4 MACRO ALGORITHM FOR RT_MOVE FUNCTION

Step 0 Start.

Step 1. if(proc_time > stip_proc_time) then

- proc_time = 0.0; and
- change the status of overtaking and yielding flags.

Step 2 Call right_move function.

Step 3 Get x_dist_right, y_dist, move_flag, l_o_dist, l_o_idn, l_o_vt;
where x_dist_right = right displacement of vehicle in right direction
y_dist = maximum y distance which vehicle can move in forward direction
move_flag = movement flag
l_o_dist = left displacement of vehicle required in x direction to perform overtaking from left direction
l_o_idn = left overtaken vehicle identity number
l_o_vt = left overtaken vehicle type

Step 4 If (move_flag = FALSE) go to Step 8.

Step 5 Call function coord_calc;
coord_calc calculates distance moved by the vehicle in y direction, speed and acceleration for given value of y_dist.

Step 6 Change position of vehicle by x_dist and y_dist, assign vehicle to new grid elements by vehicle assign procedure. Which assigns vehicle new attributes to new grid element and make boolean variables check and flag as TRUE.

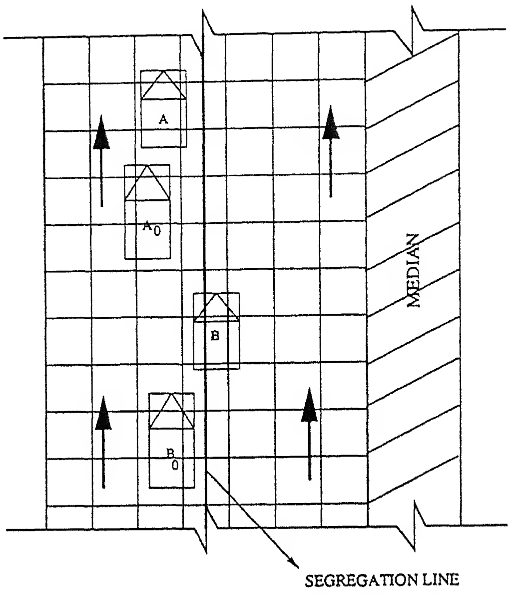

Figure A.9: Behaviour of a Vehicle During Overtaking from the Right of Overtaken Vehicle near Segregation Line (Right Move Sub-Model)

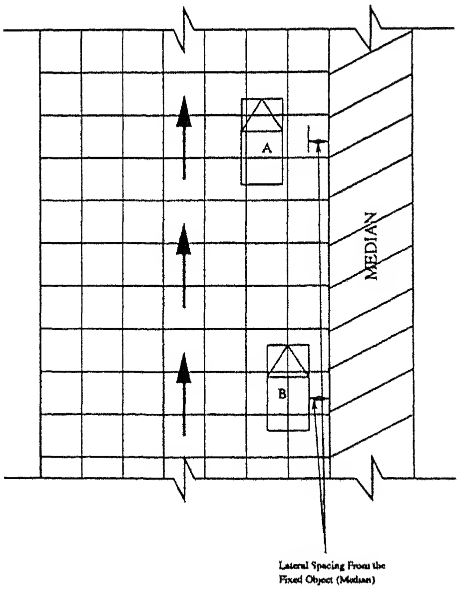

Figure A.10: Effect of Lateral Space Required by the Vehicle from Fixed Object (Median) during Right Movement (Right Move Sub-Model)

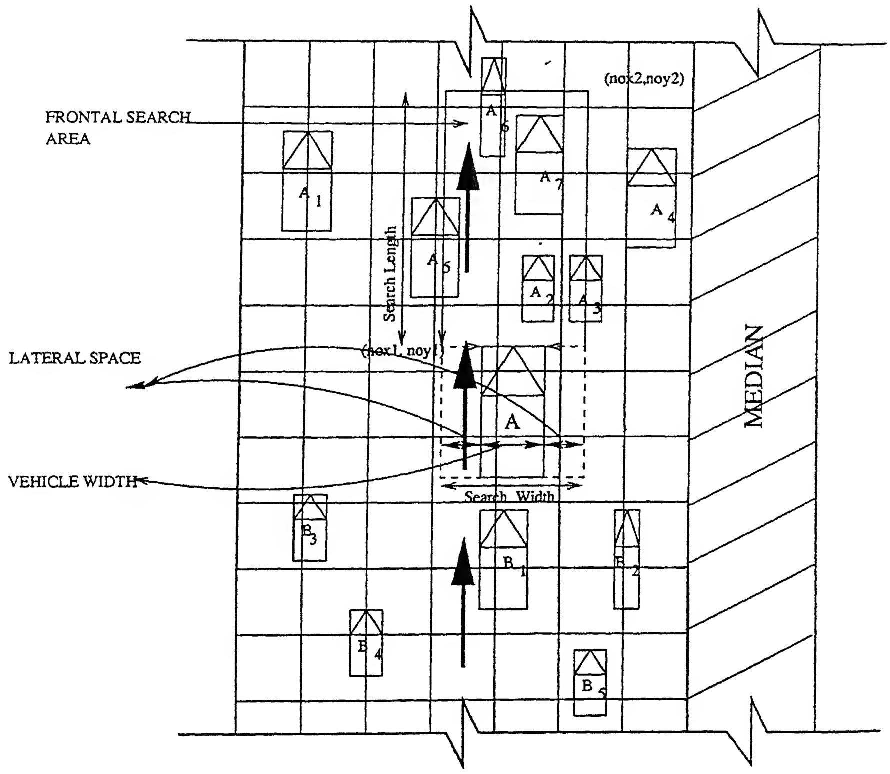

Figure A.11: Scanning Frontal Search Area for Overtaking Decision

Step 5b. Storing into temporary storage by checking vehicle is lying in area infront of current vehicle. If(lying_flag = FALSE) then go to Step 6. Calculate headway according to type of headway calculation adopted in the model.

if ((Difference in position y of two vehicles) $\leq$ (interaction_constant*headway)
then interaction_flag = TRUE
else interaction_flag = FALSE.

Calculate probability of overtaking of current vehicle with vehicle infront by difference in speed and inter-vehicular lateral spacing method; take minimum of two probabilities.

If (generated probability $\leq$ required probability)
then
prob_flag = TRUE
else
prob_flag = FALSE.

Step 6. Vehicles which are to be stored into temporary storage are A_2, A_3, A_5, A_6 and A_7 (Figure A.11). Vehicle attributes which are stored are as follows : position x, position

y, speed, group number, vehicle type, spacing flag, interaction flag, probability flag and identity number. Do sorting of vehicles which are stored into temporary storage; get right and left most vehicle which can be overtaken having interaction and probability flag from sorted vehicles for overtaking from right and left side respectively.

Step 7. Register x_coordinate, y_coordinate, group number, speed, vehicle type and identity number into temporary storage for the left and right overtaken vehicle.

Step 8. If (left overtaking flag is TRUE) then calculate left overtaking distance(Displacement in X Direction) by solving overtaking speed polynomial in which overtaking vehicle speed is a function of overtaking vehicle speed and inter-vehicular lateral spacing by newton raphson method. Get required x displacement in right direction.

Step 9. If (prob_flag = TRUE and *r_flag = TRUE) then go to Step 10 else go to Step 21.

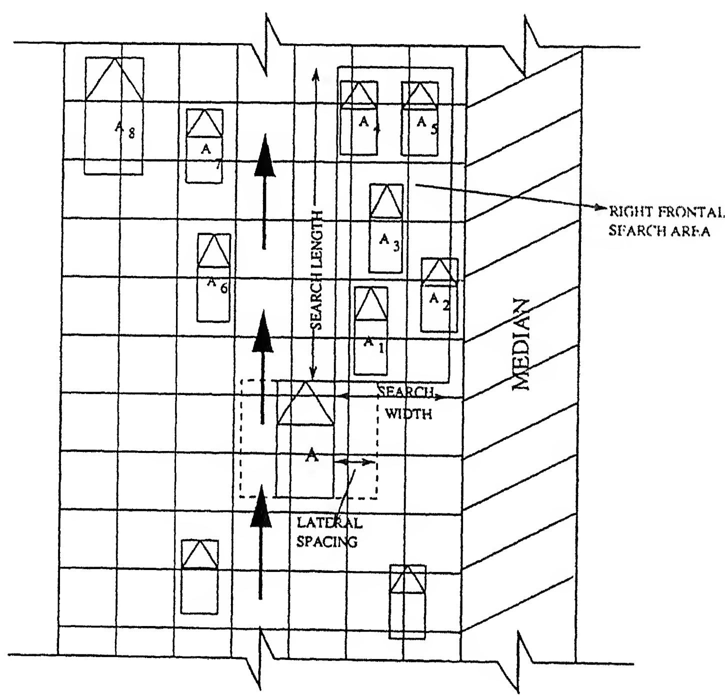

Figure A.12: Scanning Right Frontal Search Area for Calculating Possible Right Movement

Step 10. Get right frontal search area and check the same. Store vehicle into temporary storage, which are present in the search area. From Figure A.12 vehicles which are lying inside search area and stored in temporary storage are A_1, A_2, A_3, A_4 and A_5. Vehicle attributes which are stored are as follows: position x, position y, separation in x-direction, separation in y-direction, front headway, power weight ratio, interaction flag, spacing flag, veh_type, and group number.

Step 11. Calculate right_x1 and *y_dist on the basis of vehicle stored in temporary storage.

Step 12. Calculate check_distance, where,
check_distance = width of the vehicle + lateral space required on one side.

Step 13. if (right_x1 < check_distance) then go to Step 14 else go to Step 16.

Step 14. Get frontal strip search area and check the same. As shown in Figure A.13 vehicles stored in temporary storage are A_1 and A_2. Stored vehicle attributes are same as in right frontal area case. Analyse temporary storage; if it is required to modify *y_dist and right_x1 modify it.

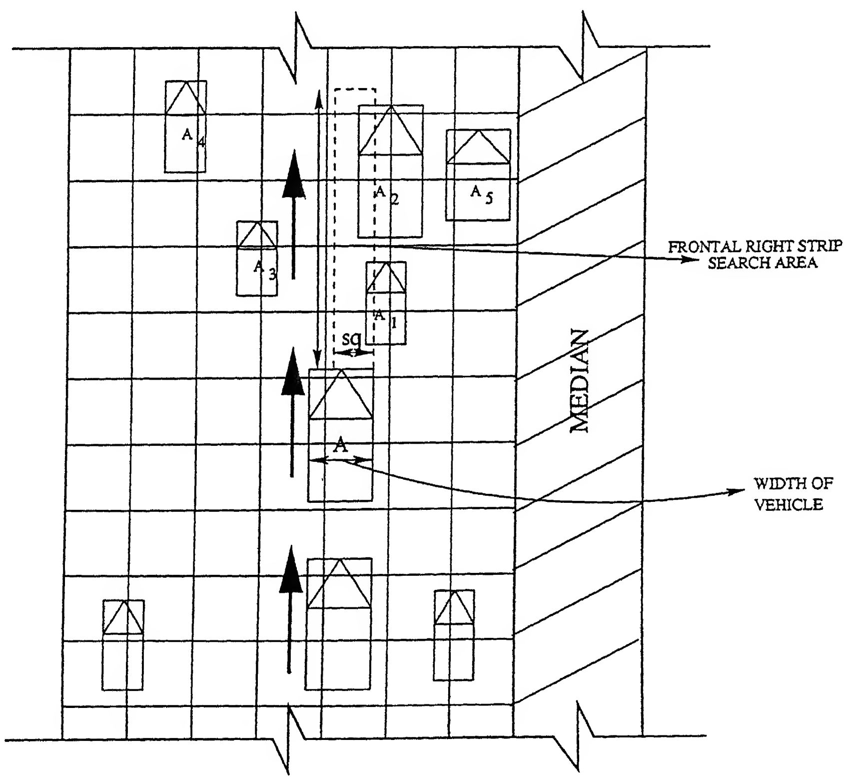

Figure A.13: Scanning Frontal Strip Search Area after Considering Possible Right Movement of the Vehicle by Checking Right Frontal Search Area

Step 15. If(right_x1 $\leq$ 0.0) then
{ *r_flag = FALSE;
go to Step 21;
}
else

```
{
r_flag = TRUE;
go to Step 16;
}
```

Step 16. Get right rear search area and check the same. Refer to Figure A.14. Store attributes of the vehicles present in the right frontal search area. As shown in Figure A.14 vehicles stored in temporary storage are B_1, B_2, B_3, and B_4. Stored attributes of the vehicles are same as right front area case. Based on stored vehicles calculate probable right displacement.

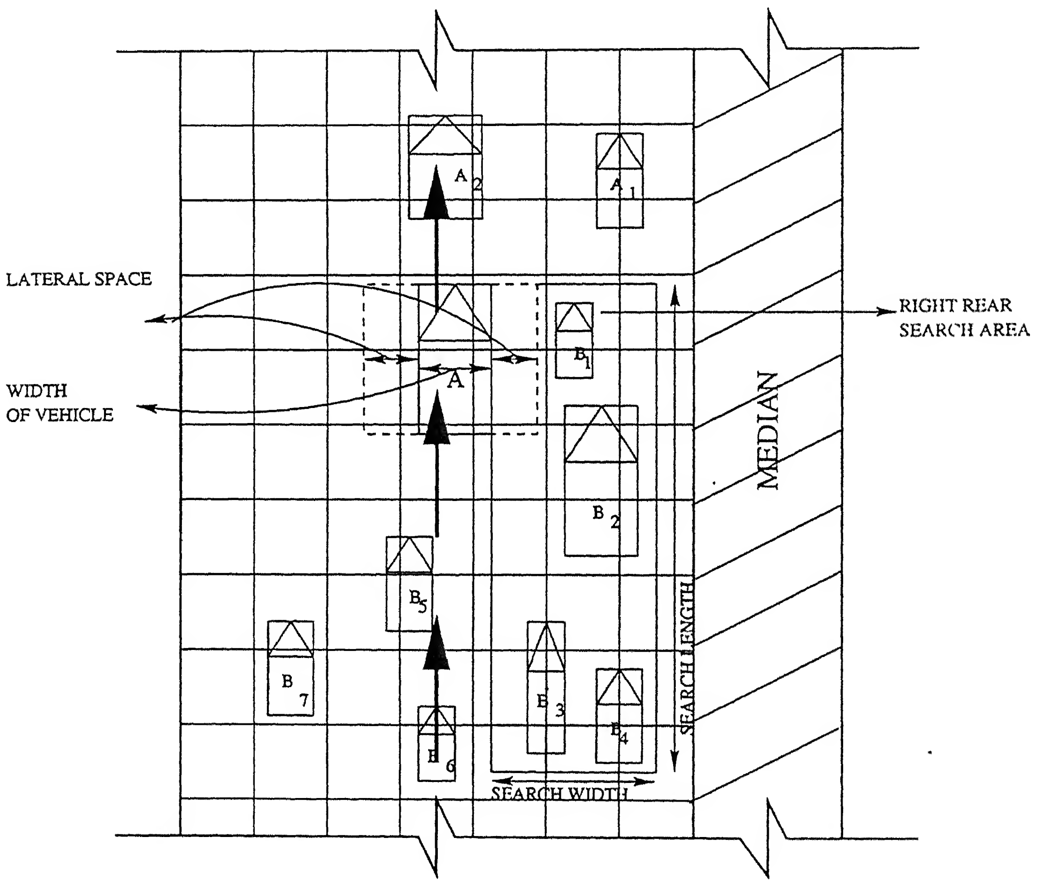

Figure A.14: Scanning Rear Search Area for Calculating Possible Right Movement

Step 17. if(right_x1 $\leq$ right_x2)
x_dist = right_x1
else
x_dist = right_x2 Where right_x1 is a maximum possible x displacement obtained from

checking right front area and right_x2 is a maximum possible displacement obtained from checking right rear area.

Step 18. Remodify the *x_dist on the basis of segregation distance, right most boundary of the road, distance from the fixed object (centrally raised median) and distance required for overtaking (req_x_dist).

Step 19. If (*x_dist < req_x_dist)
then
modify (req_x_dist) distance required by the current vehicle to overtake from right direction; req_x_dist = req_x_dist - *x_dist;
else
req_x_dist = 0.0.

Step 20. If(req_x_dist==0.0) then ovt_r_flag = FALSE.

Step 21. Stop.

A.6 MACRO ALGORITHM FOR FW_MOVE FUNCTION

Step 0. Start.

Step 1. if(proc_time¿stip_proc_time) then

- proc_time = 0.0; and
- change the status of overtaking and yielding flags.

Step 2. Call forward_move function.

Step 3. Get x_dist, const_flag, y_dist, vel, acce;

where x_dist	=	x displacement of vehicle in x direction
y_dist	=	y displacement of vehicle in y direction
const_flag	=	constrained flag
vel	=	speed calculated when vehicle is constrained
acce	=	acceleration calculated when vehicle is constrained

In a constrained situation speed and acceleration(acce) is calculated by car following model or space headway polynomial approach.

Step 4. If (const_flag = FALSE) then call function coord_calc, coord_calc calculates distance moved by the vehicle in y direction, speed and acceleration for given value of y_dist.

Step 5. Move vehicle by x_dist = 0 and y_dist; assign vehicle to new grid elements by vehicle_assign(); assigns vehicle attributes to new grid element and makes boolean variables check and flag as TRUE.

Step 6. Assign previous grid elements occupied by the vehicle as

road[i][j].veh[g_no] = NULL;
road[i][j].check[g_no] = TRUE;
road[i][j].flag[g_no] = FALSE;

where i,j represents grid number and g_no represents number of vehicle.

Step 7. Stop.

A.7 MACRO ALGORITHM FOR FORWARD_MOVE FUNCTION

Step 0. Start.

Step 1. Get the following:

- corresponding group number of current vehicle type;
- maximum acceleration capability at the current speed;
- lateral space required by the vehicle using lateral space polynomial; and
- lateral clearance from the fixed objects.

Step 2. Get frontal search area (Reference can be made to Figure 3.13) to be scanned and check the same. Frontal area search process can be made clear by referring to Figure A.15. Vehicles A_1, A_2, A_3, A_4, A_5, A_6, and A_7 are ahead of vehicle A, but only vehicle A_1, A_2, A_3, A_4, and A_5 are present in the frontal search area. Store vehicle attributes into temporary storage. Out of these selected five vehicles, vehicles A_4 and A_5 will not be considered for analysis because they are not present directly infront of vehicle A. Only three vehicles A_1, A_2 and A_3 will be considered for decision making. Store vehicle attributes into temporary storage.

Step 3. If there are more than one vehicle in front of the current vehicle (multiple following), then it is necessary to select one vehicle to which current vehicle is following. As in the existing literature of vehicles following, it is assumed that vehicles follow only one vehicle. Therefore it is necessary to develop a some criteria to select one of the vehicles in case of multiple following. It was felt that there is a need of developing car following theory (multiple vehicle following theory) in the case of multiple following.

In the present work two criterion are proposed. These are follows:

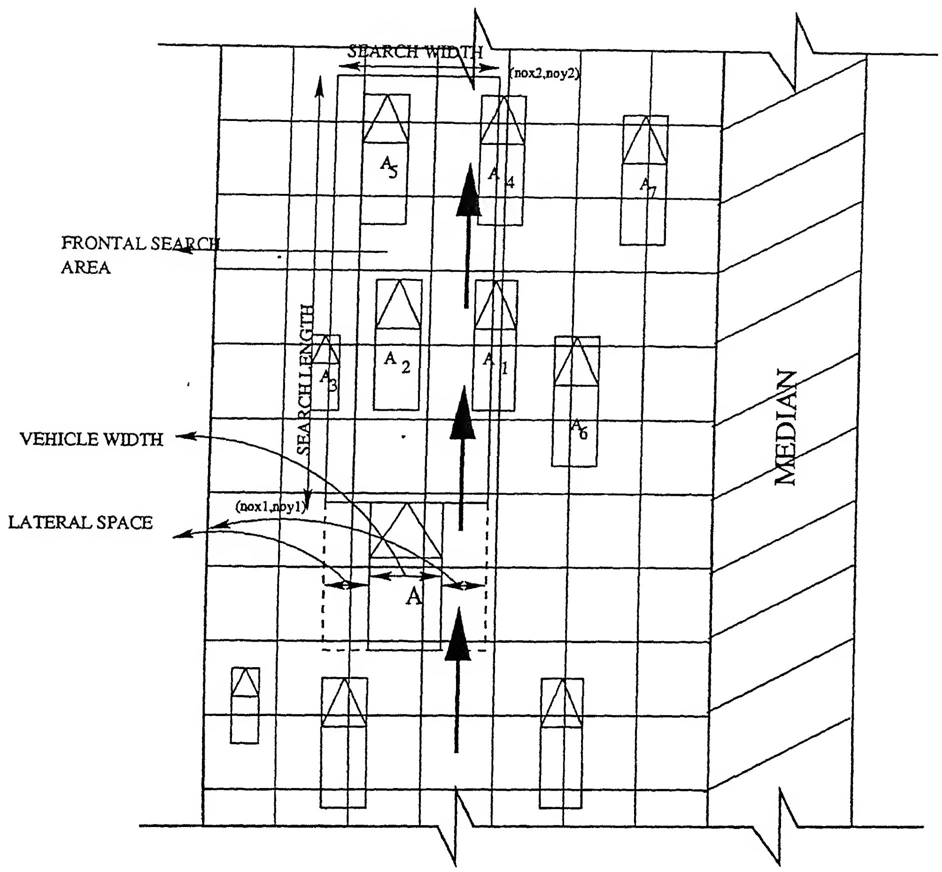

Figure A.15: Checking Area Infront of the Vehicle for Calculating Possible Forward Movement of the Vehicle by Considering Vehicles Which are Present in Search Area (Forward Move Sub-Model)

Criteria I Select that vehicle which is nearest to the current vehicle. If two vehicles have the same position along the length of the road then choose that vehicle whose speed is less (it is obvious that vehicle having lesser speed will require more space headway with the current vehicle).

Criteria II Calculate space headway required by the current vehicle with all the vehicles which are directly in front and present in the influence area. Evaluate the value of the following expression for all the vehicles which are interacting with the current vehicle.
difference = $((lv_y$ - $fv_y)$ - $(vel_{fv}$*deltat + required space headway))

where lv_y = lead (front interacting) vehicle y coordinate;
fv_y = following (rear vehicle which is current vehicle in this case) vehicle y coordinate; and
vel_{fv} = speed of following vehicle.

Select that vehicle whose difference is minimum. If two vehicles have the same difference, then that vehicle will be selected which is nearest to the current vehicle. There may be a case in which two vehicle having the same difference and same positioning along the road length. In this case left most vehicle can be taken for decision making to determine whether current vehicle is constrained or free flowing. And also selected vehicle will be used in car following model or space headway polynomials for getting following vehicle's acceleration rate. Acceleration rate obtained by car following model or space headway polynomials can be further modified by considering space headway required by all the vehicles in emergency regime.

Step 4. Check vehicle is constrained or unconstrained. Assign const_flag (constrained flag) accordingly.

Step 5. If(const_flag = FALSE)
{ calculate vehicle y_displacement by free flow model and go to Step 9. } else goto Step 6.

Step 6. If(Overtaking constant for given current vehicle type to overtake from the left is TRUE) then (overtaking constant TRUE means for a given vehicle type, it is allowed to overtake from the left also)
{
Call left_move function;
get x_displacement and y_displacement of the vehicle and also value of *l_flag;
}
else
{
l_flag = FALSE;
(Left overtaking is not possible)
}

Step 7. If(*l_flag=FALSE) goto Step 8
else goto Step 9.

Step 8. Use car following model or fitted space headway polynomials to get vehicle y_displacement (in this case vehicle x_displacement = 0)

Step 9. Stop.

Appendix B

DATA SUPPLEMENTARY TO CHAPTER 4: MODEL FOR ANIMATION OF SIMULATED TRAFFIC FLOW

B.1 MACRO ALGORITHM FOR MAIN GRAPHICS PROGRAM

Step 1. Start.

Step 2. Display demo programs.

Step 3. Read :

1. Traffic data
2. Road data
3. Other relevant information

Step 4. Open Starbase Graphics system.

Step 5. Define and initialise view volume.

Step 6. Open button box, mouse, and key board.

Step 7. Select animation session, or graph session, or exit.

Step 8. If(it is graph session) go to Step 10; else if(it is animation session) go to Step 9; else (exit) go to step 12.

Step 9. Go to animation menu; get animated views of traffic; go to step 11.

Step 10. Go to graph drawing menu. Get time-distance, time-velocity, and time-acceleration graphs.

Step 11. Go to Step 8.;

Step 12. Display exit demo programs.

Step 13. Close button box, key board and mouse.

Step 14. Close Starbase graphics.

Step 15. Stop.

B.2 LISTING OF GRAPHICAL SUBROUTINES USED FOR ANIMATION AND GRAPHICAL REPRESENTATION OF TRAFFIC FLOW PARAMETERS

B.2.1 Data Reading Functions

function read_data_veh
function definition void read_data_veh() {—}
It reads data of left and right major roads vehicles during simulation run. Data are vehicle type, identity no, vehicle actual lateral and longitudinal coordinates, vehicle transformed lateral and longitudinal coordinates, time etc..

function read_data_inter
fuction definition is same as read_data_veh.
It reads data of minor road vehicles of an intersection during simulation run, data are vehicle type, identity no, intersection no, actual and transformed vehicle lateral and longitudinal coordinates.

function read_seg_wid
function definition void read_seg_wid() {—}
It reads segregation width of various vehicle types on left and right major roads.

function read_data
function definition void read_data(){—}
It reads various attributes such as left and right pedestrian ways width, road shoulders width, road width, median width, road formation level, minimum and maximum lateral and

longitudinal coordinates of a simulated road area.

function read_veh_dim
function definition void read_veh_dim(){—-}
Above function reads vehicle length, width, and height of various vehicle types.

B.2.2 Functions for Displaying Simulation of Traffic in Three or Two Dimensions

Starbase.c.h.
File contains all starbase graphical subroutines.
Define.c File contains all the constant declaration used in this graphics software package.
glo_var.c File contains all the global variable declarations.
define-func.c It contains all the function declaration.

function pol_coor
function definition void pol_coor(coor[][3]){—-}
coor[][3] is a three dimensional array for reading verticies of a polygon.

function st_gopen
function definition void st_gopen(){—-}
Opens starbase graphics library. .

function initialise_l
function definition void initialise_l(){—-}
Initialises left major road vehicle storage. Function definition and discription for function initialise_r is same as initialise_l.

function new_coord_sys
function definition void new_coord_sys(xmin,ymin,zmin,xmax,ymax,zmax){—-}
Function defines new three dimensional coordinate system in which xmin, ymin, zmin give minimum x, y, z value of volume and xmax, ymax, zmax give maximum x, y, z value of volume.

function rectangl_comp
function definition void rectangl_comp(f_c,a[4][3]){—-}
Draws rectangle in three dimension where f_c gives a rectangle color (1 to 256) and a[4][3] represent rectangle verticies.

function lane_marking
function definition void function lane_marking_m(x_start,y_start,z_start,x_end,y_end,z_end){—
-}

Draws lane marking in three dimension for left and right simulated major road,
where x_start, y_start, z_start = minimum value of lane marking area
x_end, y_end, z_end = maximum value of lane marking area

function close_graphics
function definition void close_graphics(){—}
This function close starbase graphics library, mouse locator, and button box.

function open_button_knob
function definition void open_button_knob(){—}
Function activates button box and knob box device.

function open_mouse
function definition void open_mouse(){—}
Activates mouse locator.

function open_keyboard
function definition void open_keyboard(){—}
Function helps in opening Keyboard and closing mouse locator.

function accept_pt
function definitioncoord_accept_pt(){—}
It returns northing and easting of mouse locator.

function give_choice
function definition int give_choice(){—}
Returns integer value according to area of the screen clicked by the mouse and returned value is used in menu operations.

function give_choice1,———,give_choice4
Description and definition is same as give_choice.

function zoom function definition void zoom(){—}
Used for zooming certain area of a screen.

function help
function definition void help(){—}
Gives on screen help available in this software package.

function main_menu, front_menu, menu1,———,menu6.
function main_menu()
function definition void main_menu(argc,argv) int argc; char **argv; {—}
Above function gives menus at various stages in this graphics software package with facility

of input from button box, key board, mouse one at a time. Function definition of front_menu, menu1,——-, menu6 is same as main_menu.

function camera_viewing
function definitionvoid camera_viewing(cp_x, cp_y, cp_z, cr_x, cr_y, cr_z, c_ang, c_fr, c_bck, pl, pm, pn, cam_proj){—–}
Function helps in fixing camera position in three dimensional space and gets other required attributes of camera.

where cp_x, cp_y, cp_z	=	x, y, and z positions of camera in three dimension
cr_x, cr_y, cr_z	=	x, y, and z positions of camera reference point
c_ang	=	cone angle (vision angle) of camera
c_fr, c_bck	=	camera front and back clipping planes
pl, pm, pn	=	Direction cosines of line joining camera position with camera reference point
cam_proj	=	type of camera projection (parallel or perspective)

function make_grid3d
function dfinition void make_grid3d(x1,y1,z1,x2,y2,z2,deltax,deltaz){—–}
Function makes grid in two dimension. where x1, y1, and z1 and x2, y2, and z2 are diagonally opposite vertices of grid area.

function make_grid2d
Function definition and discription is quite similar to make_grid3d.

function view_2d
function definition void view_2d(x_starts, y_starts, x_maxs,y_maxs){—–}
Above subroutine gives two dimensional animated view of traffic on simulated roadway.

where x_starts, y_starts	=	minimum x and y coordinates of two dimensional view area
x_maxs, y_maxs	=	maximum x and y coordinates of two dimensional view area

function l_roa_veh, r_roa_veh
function definition, function definition of r_roa_veh is same as l_roa_veh. void l_roa_veh(){——}
It draws vehicles in three dimension at any time t on left major road.

function d_view_rm
function definition void d_view_rm(x_start, y_start, z_start, x_end, y_end, z_end, t_start, t_end) {—–}
Above function displays three dimensional animated view of simulate traffic on roadway. It uses various starbase subroutines and functions discribed in this package, all the required features of road vehicles are clearly visible. Special shading effect and light sources are also used in this function. There is a special facility for fixing observer (camera position) and it gives different views of simulated traffic such as front view, side view, plan etc.

where x_start, y_start, z_start	=	minimum x,y and z coordinates of three dimensional simulated area
x_end, y_end, z_end	=	maximum x, y and z coördinates of three dimensional simulated area
t_start	=	starting simulation time
t_end	=	ending simulation time

function view_3d
function definition void view_3d(x_start, y_start, z_start, x_end, y_end, z_end) {—–}
Subroutine calls function d_view_rm with the help of menu and it also gives facility for fixing new camera position. where x_start, y_start, and z_start are minimum x, y, and z coordinates respectinely and x_end, y_end, and z_end are maximum x, y, and z coordinates respectively.

function exiter
function definitionvoid exiter(){—–}
Above function helps in exiting software package with some message.

function ProcessKeyStroke
function definition void ProcessKeyStroke(Key){—–}
ProcessKeyStroke returns integer value for a Button Box.

function hor_cylinder
function definition void hor_cylinder(x_cent, y_cent, z_cent, l, dia, d_theta, phc_col, hc_mtif){—
—}
where x_cent, y_cent, and z_cent are centre coordinates of horizontal cylinder; l is length of horizontal cylinder; dia is diameter of horizontal cylinder; phc_col is color of horizontal cylinder; and hc_mtif is boolean variable (if it is true then the horizontal cylinder is drawn along the major road and when it is false then it will be drawn along the minor road of intersection. hor_cylinder draws horizontal cylinder in three dimensional space, which is used for drawing various vehicle components.

function ver_cylinder, inclined_cylinder_f, inclined_cylinder_b. Function definition and passing variable discription is same as function hor_cylinder. They are used for drawing vertical cylinder, inclined cylinder in forward and backward directions in three dimensional space, these are used for drawing various vehicle components.

function bicycle_m
function definition void bicycle_m(x_cent, y_cent, z_cent,l1,b1,h1,bi_col,p_flag){—–}
where x_cent, y_cent, and z_cent are centre coordinates of a bicycle; l1, b1, and h1 are length, breadth, and height respectively; w_dia is wheel diameter; bi_col is bicycle colour; and p_flag is boolean variable (if it is true then bicycle is drwan in forward direction else in backward direction along the major road. Above function draws bicycle in three dimensional space along the major road, which is used for animation of simulated traffic.

function mop_sccot_mot_m, three_wheeler_m, car_m, van_m, jeep_m, tempo_m, truck_m, push_cart_m, buffalo_cart_m, lcv_m, horse_cart_m, tractor_m, sm_push_cart_m.

function definition function definition and passing variables are same as in function bicycle_m. Above function draws all type of motorized and non-motorized vehicles present in urban heterogeneous traffic mix.

B.2.3 Functions for Displaying Vehicle Trajectories

function tics
function definition void tics(parameter list)
Function draws tics for axis (x or y) of the graph (time-distance, time-velocity, and time-acceleration).

function veh_inf
function definition void veh_inf(parameter list)
Function prints vehicle attributes in one window, it includes vehicle type, vehicle name, and identity no.

function road_inf
function definition void road_inf(parameter list)
Function prints road informations in one window, it includes direction of flow, road width, curvature, roughness, and gradient.

function road_draw
bf function definition void road_draw(parameter list)
Function draws road for moving vehicle during vehicle traffic flow parameters display.

function time_display function definition void time_display
Displays simulation current time, start time, and end time.

function gr_dr_session
function definition void gr_dr_session()
Graph draw session: It gives interactive menus for displaying vehicle traffic flow parameters. Traffic flow parameters (vehicle trajectories during simulation run) which can be displayed are as follows:

1. time-distance,
2. time-velocity, and
3. time-acceleration.

function make_graph
function definition void make_graph(parameter list)
Draws graph for given input data. Graphs include the following:

1. Tic marks on X and Y axis
2. Labeling of X and Y axis
3. Titles of X and Y axis
4. Curves
5. Minimum and maximum X and Y range

function data_sort
function definition void data_sort(parameter list)
Used for arranging data in ascending and descending order.

Appendix C

DATA SUPPLEMENTARY TO CHAPTER 8: SENSITIVITY ANALYSIS

Table C.1: No. of Overtakings for Different Combinations of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - I
Non-Motorised Vehicles Road Usage Restricted to 3.50 m (one lane)

	No. of Overtakings								
Flow (vph)	Wide MV ov. Wide MV	Wide MV ov. Narrow MV	Narrow MV ov. Wide MV	Narrow MV ov. Narrow MV	Wide MV ov. Wide NMV	Wide MV ov. Narrow NMV	Narrow MV ov. Wide NMV	Narrow MV ov. Narrow NMV	Total
600	42	6	60	3	596	1634	531	1377	5421
900	66	10	84	5	803	2339	735	2000	7732
1200	78	21	97	14	1086	3032	893	2529	9971
1800	116	31	170	30	1506	4264	1249	3619	14228
2400	176	61	206	43	1947	5425	1585	4520	18031
3000	288	79	314	56	2316	6445	1823	5554	21526
3600	356	86	460	126	2555	7130	2082	6119	24908
4200	436	107	678	148	2492	6809	2197	6473	24535

Table C.2: Mean Journey Speeds of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - I
Non-Motorised Vehicles Road Usage Restricted to 3.50 m (one lane)

Flow (vph)		Journey Speed						
		Car/ Van/ Jeep (m/sec)	Tempo/ Auto Rickshaw (m/sec)	Bus/ LCV (m/sec)	Motorised Two Wheelers (m/sec)	Bicycle (m/sec)	Cycle Rick-shaw (m/sec)	All Vehicles (m/sec)
Sample Size		80 *75	200 *186	40 *35	240 *226	800 *751	232 *220	1600 *1500
Free Speed	Mean	12.88	8.91	11.62	12.45	4.50	4.43	6.79
	St. Dev.	1.01	1.13	1.27	1.44	0.68	0.63	3.51
600	Mean	11.63	8.41	10.66	11.12	4.43	4.10	6.39
	St. Dev.	1.52	0.95	1.17	1.60	0.64	0.57	2.72
900	Mean	10.66	8.06	9.82	10.35	4.41	4.08	6.15
	St. Dev.	1.85	1.08	1.03	1.62	0.63	0.56	2.76
. 1200	Mean	10.15	7.83	9.32	9.69	4.36	4.06	5.05
	St. Dev.	1.76	1.08	1.33	1.66	0.61	0.58	2.56
1800	Mean	8.88	7.05	8.40	8.56	4.22	3.96	5.52
	St. Dev.	1.57	1.20	1.29	1.65	0.57	0.54	2.15
2400	Mean	7.97	6.45	7.57	7.76	4.05	3.80	5.15
	St. Dev.	1.24	1.10	1.13	1.38	0.50	0.49	1.84
3000	Mean	7.13	5.80	6.85	6.96	3.88	3.66	4.78
	St. Dev.	1.16	0.83	1.24	1.22	0.48	0.44	1.54
3600	Mean	6.38	5.22	5.97	6.12	3.71	3.51	4.41
	St. Dev.	0.96	0.94	1.01	1.08	0.41	0.37	1.27
4200	Mean	5.40	4.44	4.78	5.18	3.43	3.31	3.93
	St. Dev.	1.05	0.79	0.93	0.98	0.35	0.32	0.98

* After excluding statistics of first 100 vehicles.

Table C.3: Acceleration Noise of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - I
Non-Motorised Vehicles Road Usage Restricted to 3.50 m (one lane)

	Acceleration Noise						
Flow (vph)	Car/Van/ Jeep (m/sec^2)	Tempo/ Auto Rickshaw (m/sec^2)	Bus/ LCV (m/sec^2)	Motorised Two Wheelers (m/sec^2)	Bicycle (m/sec^2)	Cycle Rickshaw (m/sec^2)	All Vehicles (m/sec^2)
600	0.299	0.133	0.635	0.116	0.043	0.043	0.092
900	0.409	0.016	0.884	0.193	0.068	0.064	0.137
1200	0.461	0.222	0.978	0.229	0.094	0.097	0.169
1800	0.6067	0.288	1.059	0.292	0.164	0.170	0.243
2400	0.7279	0.353	1.186	0.339	0.229	0.229	0.308
3000	0.793	0.396	1.223	0.375	0.285	0.287	0.359
3600	0.854	0.430	1.119	0.424	0.350	0.346	0.419
4200	0.913	0.501	1.154	0.474	0.424	0.400	0.478

Table C.4: Traffic Concentration for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - I
Non-Motorised Vehicles Road Usage Restricted to 3.50 m (one lane)

	Concentration							
Flow (vph)	No. of Vehicle per km		Road Occupancy (percent of road area)			Influence Area (percent of road area)		
	Mean	Max.	Mean	S.D.	Max.	Mean	S.D.	Max.
600	32	52	0.87	0.39	2.02	4.66	1.66	9.57
900	48	70	1.46	0.52	2.72	7.27	1.93	11.49
1200	66	100	2.01	0.63	3.86	9.65	2.37	15.73
1800	106	140	3.25	0.78	4.84	14.82	2.91	21.55
2400	152	182	4.72	0.88	6.54	20.21	3.45	26.50
3000	194	216	6.28	1.27	9.06	25.15	4.15	31.09
3600	254	284	8.50	1.20	11.13	32.20	3.74	39.19
4200	328	372	11.80	1.11	13.36	41.88	3.30	47.40

Table C.5: Mean Journey Speeds of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - II
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)		Journey Speed						
		Car/ Van/ Jeep (m/sec)	Tempo/ Auto Rickshaw (m/sec)	Bus/ LCV (m/sec)	Motorised Two Wheelers (m/sec)	Bicycle (m/sec)	Cycle Rick-shaw (m/sec)	All Vehicles (m/sec)
Sample Size		160 *153	240 *225	80 *77	320 *297	560 *521	240 *227	1600 *1500
Free Speed	Mean	12.98	8.96	11.76	12.39	4.50	4.20	7.93
	St. Dev.	1.19	1.09	1.35	1.47	0.67	0.64	3.83
600	Mean	10.89	8.29	10.64	10.73	4.49	4.19	7.23
	St. Dev.	1.59	1.03	1.32	1.69	0.66	0.63	3.14
900	Mean	10.10	7.85	10.03	9.76	4.47	4.16	6.84
	St. Dev.	1.52	1.07	1.20	1.66	0.66	0.63	2.78
1200	Mean	9.47	7.56	9.74	9.20	4.43	4.14	6.59
	St. Dev.	1.53	1.04	1.43	1.56	0.65	0.62	2.56
1800	Mean	8.17	6.74	8.28	7.83	4.35	4.08	5.95
	St. Dev.	1.30	0.99	1.17	1.17	0.63	0.62	1.96
2400	Mean	7.11	5.84	6.96	6.85	4.25	3.99	5.38
	St. Dev.	0.99	0.91	1.09	1.05	0.60	0.57	1.52
3000	Mean	6.34	5.27	5.96	6.09	4.09	3.83	4.95
	St. Dev.	0.82	0.74	1.03	0.83	0.55	0.51	1.21
3600	Mean	5.43	4.49	5.09	5.20	3.84	3.66	4.41
	St. Dev.	0.71	0.63	0.73	0.74	0.45	0.44	0.84
4200	Mean	4.82	3.96	4.27	4.55	3.55	3.45	3.96
	St. Dev.	0.68	0.51	0.60	0.62	0.37	0.39	0.71

* After excluding statistics of first 100 vehicles.

Table C.6: Acceleration Noise of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - II
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)	Car/Van/ Jeep (m/sec^2)	Tempo/ Auto Rickshaw (m/sec^2)	Bus/ LCV (m/sec^2)	Motorised Two Wheelers (m/sec^2)	Bicycle (m/sec^2)	Cycle Rickshaw (m/sec^2)	All Vehicles (m/sec^2)
600	0.498	0.140	0.539	0.168	0.019	0.022	0.143
900	0.600	0.214	0.678	0.246	0.039	0.049	0.198
1200	0.632	0.251	0.810	0.280	0.065	0.078	0.234
1800	0.712	0.318	0.962	0.338	0.116	0.120	0.296
2400	0.816	0.377	1.024	0.382	0.177	0.177	0.352
3000	0.857	0.410	1.008	0.417	0.235	0.232	0.400
3600	0.916	0.466	1.039	0.467	0.316	0.294	0.463
4200	1.006	0.506	0.926	0.508	0.402	0.369	0.518

Table C.7: Traffic Concentration for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - II
Unrestricted Road Usage for Non-Motorised Vehicles

	Concentration							
Flow (vph)	No. of Vehicle per km		Road Occupancy (percent of road area)			Influence Area (percent of road area)		
	Mean	Max.	Mean	Max.	S.D.	Mean	Max.	S.D.
600	28	52	1.10	2.51	0.47	5.22	9.92	1.84
900	45	70	1.84	3.33	0.63	8.21	14.37	2.46
1200	61	104	2.46	3.79	0.64	10.80	18.07	2.52
1800	95	128	3.88	6.03	1.06	16.01	23.25	3.67
2400	136	174	5.88	8.07	0.99	22.49	30.11	3.45
3000	182	232	8.13	10.53	1.23	29.42	36.70	4.01
3600	249	280	11.51	13.73	1.73	39.07	45.68	4.99
4200	296	372	13.65	15.27	1.61	44.91	50.52	4.43

Table C.8: No. of Overtakings for Different Combinations of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - II
Unrestricted Road Usage for Non-Motorised Vehicles

	No. of Overtakings								
Flow (vph)	Wide MV ov. Wide MV	Wide MV ov. Narrow MV	Narrow MV ov. Wide MV	Narrow MV ov. Narrow MV	Wide MV ov. Wide NMV	Wide MV ov. Narrow NMV	Narrow MV ov. Wide NMV	Narrow MV ov. Narrow NMV	Total
600	96	17	81	13	877	1640	597	1243	5276
900	127	29	114	27	1247	2322	833	1745	7517
1200	173	41	157	33	1577	3046	1074	2234	9794
1800	299	97	207	63	2054	4028	1425	3016	13288
2400	452	163	373	104	2388	4569	1677	3471	15766
3000	697	161	555	110	2648	4990	1962	3902	18066
3600	895	225	784	209	2587	4611	2001	3977	18659
4200	1085	266	1014	286	2401	4468	2002	3990	18998

Table C.9: Mean Journey Speeds of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - III
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)		Journey Speed Car/ Van/ Jeep (m/sec)	Tempo/ Auto Rickshaw (m/sec)	Bus/ LCV (m/sec)	Motorised Two Wheelers (m/sec)	Bicycle (m/sec)	Cycle Rick-shaw (m/sec)	All Vehicles (m/sec)
Sample Size		240 *217	320 *303	80 *74	400 *380	400 *378	160 *148	1600 *1500
Free Speed	Mean	13.09	8.91	11.49	12.22	4.55	4.15	8.92
	St. Dev.	0.94	1.11	0.948	1.40	0.70	0.64	3.71
600	Mean	11.07	8.44	10.43	10.45	4.53	4.13	8.01
	St. Dev.	1.56	1.09	1.34	1.58	0.69	0.63	3.02
900	Mean	10.08	8.12	10.03	9.93	4.52	4.13	7.64
	St. Dev.	1.54	1.10	1.48	1.54	0.68	0.63	2.75
1200	Mean	9.42	7.82	9.42	9.35	4.48	4.07	7.20
	St. Dev.	1.55	1.15	1.58	1.61	0.68	0.61	2.54
1800	Mean	8.35	6.96	7.92	7.91	4.41	4.03	6.51
	St. Dev.	1.33	1.11	1.26	1.21	0.65	0.60	1.90
2400	Mean	7.17	6.18	6.73	6.87	4.29	3.95	5.83
	St. Dev.	0.96	1.00	1.08	0.96	0.60	0.56	1.51
3000	Mean	6.39	5.37	5.92	6.04	4.14	3.83	5.25
	St. Dev.	0.90	0.81	0.93	0.83	0.55	0.52	1.20
3600	Mean	5.42	4.60	5.10	5.18	3.91	3.72	4.63
	St. Dev.	0.66	0.58	0.80	0.61	0.45	0.48	0.84
4200	Mean	4.35	3.82	4.28	4.20	3.58	3.43	3.92
	St. Dev.	0.66	0.43	0.75	0.56	0.38	0.32	0.59

* After excluding statistics of first 100 vehicles.

Table C.10: Acceleration Noise of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - III
Unrestricted Road Usage for Non-Motorised Vehicles

	Acceleration Noise						
Flow (vph)	Car/Van/ Jeep (m/sec^2)	Tempo/ Auto Rickshaw (m/sec^2)	Bus/ LCV (m/sec^2)	Motorised Two Wheelers (m/sec^2)	Bicycle (m/sec^2)	Cycle Rickshaw (m/sec^2)	All Vehicles (m/sec^2)
600	0.425	0.108	0.369	0.156	0.019	0.017	0.148
900	0.471	0.155	0.349	0.198	0.037	0.033	0.179
1200	0.529	0.206	0.436	0.248	0.058	0.065	0.224
1800	0.606	0.301	0.579	0.325	0.099	0.108	0.296
2400	0.699	0.358	0.639	0.370	0.155	0.154	0.353
3000	0.767	0.417	0.641	0.411	0.215	0.202	0.405
3600	0.818	0.461	0.709	0.456	0.293	0.255	0.461
4200	0.9058	0.543	0.735	0.553	0.395	0.371	0.553

Table C.11: Traffic Concentration for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - III
Unrestricted Road Usage for Non-Motorised Vehicles

	Concentration							
Flow (vph)	No. of Vehicle per km		Road Occupancy (percent of road area)			Influence Area (percent of road area)		
	Mean	Max.	Mean	Max.	S.D.	Mean	Max.	S.D.
600	26	50	1.10	2.10	0.43	5.84	10.18	2.11
900	39	64	1.76	3.65	0.67	8.13	15.65	2.59
1200	54	82	2.47	4.35	0.65	10.87	18.20	2.53
1800	86	108	3.86	7.41	1.06	15.92	26.39	3.58
2400	133	178	5.86	10.24	1.63	22.33	36.18	5.38
3000	176	218	8.49	12.05	1.68	30.68	40.69	5.14
3600	238	284	11.81	13.89	1.30	40.19	47.36	4.00
4200	297	338	15.26	16.79	1.00	48.97	54.31	3.33

Table C.12: No. of Overtakings for Different Combinations of Vehicle Groups for Different Flow Levels

Road I (7 m Wide Road)
Traffic Composition of Level - III
Unrestricted Road Usage for Non-Motorised Vehicles

	No. of Overtakings								
Flow (vph)	Wide MV ov. Wide MV	Wide MV ov. Narrow MV	Narrow MV ov. Wide MV	Narrow MV ov. Narrow MV	Wide MV ov. Wide NMV	Wide MV ov. Narrow NMV	Narrow MV ov. Wide NMV	Narrow MV ov. Narrow NMV	Total
600	173	25	137	22	772	1680	542	1026	4744
900	211	43	181	27	1059	2312	732	1547	6655
1200	274	84	197	51	1377	2873	985	1969	8539
1800	455	143	343	85	1790	3793	1253	2549	11454
2400	683	230	495	158	2093	4314	1456	2967	13713
3000	1006	286	817	178	2239	4451	1632	3227	15303
3600	1313	340	1067	313	2118	4209	1564	3301	15897
4200	1404	413	1298	430	1409	2843	1144	2374	13167

Table C.13: Mean Journey Speeds of Vehicle Groups for Different Flow Levels

Road II (10 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)		Journey Speed Car/ Van/ Jeep (m/sec)	Tempo/ Auto Rickshaw (m/sec)	Bus/ LCV (m/sec)	Motorised Two Wheelers (m/sec)	Bicycle (m/sec)	Cycle Rick-shaw (m/sec)	All Vehicles (m/sec)
Sample Size		80 *75	200 *186	40 *35	240 *226	800 *751	232 *220	1600 *1500
Free Speed	Mean	12.88	8.91	11.62	12.45	4.50	4.43	6.79
	St. Dev.	1.01	1.13	1.27	1.44	0.68	0.63	3.51
600	Mean	11.47	8.51	10.85	11.30	4.49	4.19	6.47
	St. Dev.	1.55	1.05	1.00	1.54	0.68	0.63	3.07
900	Mean	11.23	8.42	10.63	10.85	4.49	4.17	6.37
	St. Dev.	1.39	1.04	1.22	1.55	0.68	0.63	2.93
1200	Mean	10.50	8.22	10.20	10.22	4.48	4.16	6.20
	St. Dev.	1.44	0.94	1.01	1.56	0.67	0.63	2.70
1800	Mean	9.57	7.85	9.58	9.41	4.44	4.14	5.95
	St. Dev.	1.37	1.07	1.43	1.39	0.67	0.62	2.40
2400	Mean	9.25	7.47	9.15	8.90	4.40	4.10	5.76
	St. Dev.	1.27	0.98	1.35	1.36	0.67	0.62	2.21
3000	Mean	8.44	6.84	8.47	8.01	4.32	4.03	5.45
	St. Dev.	1.01	1.03	1.22	1.22	0.66	0.60	1.89
3600	Mean	8.01	6.51	8.08	7.80	4.25	3.97	5.30
	St. Dev.	0.86	0.88	1.34	1.17	0.64	0.58	1.78
4200	Mean	7.67	6.12	7.50	7.24	4.16	3.91	5.08
	St. Dev.	0.93	0.78	1.38	1.02	0.60	0.58	1.58
4800	Mean	6.96	5.77	6.73	6.77	4.03	3.81	4.84
	St. Dev.	0.74	0.86	1.02	0.89	0.58	0.53	1.40
5400	Mean	6.35	5.21	6.23	6.21	3.89	3.71	4.55
	St. Dev.	1.04	0.83	1.35	1.03	0.52	0.51	1.25
6000	Mean	5.98	4.78	5.60	5.74	3.71	3.54	4.28
	St. Dev.	1.18	0.80	1.18	0.98	0.51	0.48	1.13
6600	Mean	6.03	4.74	5.30	5.62	3.60	3.43	4.20
	St. Dev.	1.24	0.85	0.64	0.86	0.46	0.41	1.16

* After excluding statistics of first 100 vehicles.

Table C.14: Acceleration Noise of Vehicle Groups for Different Flow Levels

Road II (10 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)	Car/Van/ Jeep (m/sec^2)	Tempo/ Auto Rickshaw (m/sec^2)	Bus/ LCV (m/sec^2)	Motorised Two Wheelers (m/sec^2)	Bicycle (m/sec^2)	Cycle Rickshaw (m/sec^2)	All Vehicles (m/sec^2)
600	0.425	0.107	0.529	0.141	0.020	0.020	0.075
900	0.462	0.117	0.569	0.162	0.022	0.020	0.089
1200	0.491	0.160	0.628	0.209	0.033	0.037	0.113
1800	0.574	0.199	0.760	0.259	0.059	0.066	0.150
2400	0.627	0.248	0.892	0.289	0.102	0.108	0.194
3000	0.681	0.307	0.946	0.332	0.140	0.149	0.237
3600	0.727	0.341	0.929	0.348	0.174	0.180	0.267
4200	0.778	0.364	1.001	0.365	0.217	0.204	0.302
4800	0.793	0.383	0.978	0.379	0.260	0.248	0.335
5400	0.852	0.423	1.005	0.405	0.308	0.291	0.377
6000	0.867	0.449	0.972	0.443	0.359	0.339	0.419
6600	0.826	0.441	1.028	0.433	0.393	0.387	0.440

Table C.15: Traffic Concentration for Different Flow Levels

Road II (10 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)	Concentration							
	No. of Vehicle per km		Road Occupancy (percent of road area)			Influence Area (percent of road area)		
	Mean	Max.	Mean	Max.	S.D.	Mean	Max.	S.D.
600	32	50	0.63	1.34	0.29	3.38	6.74	1.21
900	47	66	0.98	2.39	0.37	5.07	9.42	1.43
1200	65	96	1.38	2.77	0.44	6.91	11.70	1.82
1800	98	134	2.09	3.18	0.47	10.30	15.12	1.87
2400	136	170	2.99	4.06	0.64	14.14	17.39	2.17
3000	174	218	3.84	5.32	0.75	17.36	22.95	2.55
3600	220	268	4.98	5.78	0.50	21.89	26.16	1.96
4200	260	304	5.96	7.77	0.83	25.19	31.43	2.79
4800	304	396	6.88	9.21	1.03	28.29	37.82	4.02
5400	378	444	9.00	10.27	0.79	34.81	40.68	2.85
6000	456	472	10.81	11.18	0.31	40.22	41.63	1.00
6600	462	518	10.98	12.75	1.26	40.83	46.81	3.79

Table C.16: No. of Overtakings for Different Combinations of Vehicle Groups for Different Flow Levels

Road II (10 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

	No. of Overtakings								
Flow (vph)	Wide MV ov. Wide MV	Wide MV ov. Narrow MV	Narrow MV ov. Wide MV	Narrow MV ov. Narrow MV	Wide MV ov. Wide NMV	Wide MV ov. Narrow NMV	Narrow MV ov. Wide NMV	Narrow MV ov. Narrow NMV	Total
600	52	2	62	6	568	1595	509	1356	5407
900	78	10	92	13	839	2377	735	1982	7958
1200	93	4	110	22	1099	3053	942	2596	10378
1800	110	31	157	25	1567	4354	1306	3632	14918
2400	166	32	168	33	2003	5567	1589	4662	19263
3000	250	63	249	76	2401	6484	1810	5369	22853
3600	254	68	287	65	2715	7347	2173	6463	26640
4200	359	98	371	104	3070	8390	2492	7116	30315
4800	390	104	542	126	3291	8812	2722	7795	32796
5400	551	132	750	182	3279	8815	2882	8299	34661
6000	747	134	936	225	3516	9101	3187	8899	37223
6600	810	174	1032	274	3901	10627	3502	9651	40742

Table C.17: Mean Journey Speeds of Vehicle Groups for Different Flow Levels

Road III (14 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)		Journey Speed						
		Car/ Van/ Jeep (m/sec)	Tempo/ Auto Rickshaw (m/sec)	Bus/ LCV (m/sec)	Motorised Two Wheelers (m/sec)	Bicycle (m/sec)	Cycle Rick-shaw (m/sec)	All Vehicles (m/sec)
Sample Size		80 *75	200 *186	40 *35	240 *226	800 *751	232 *220	1600 *1500
Free Speed	Mean	12.88	8.91	11.62	12.45	4.50	4.43	6.79
	St. Dev.	1.01	1.13	1.27	1.44	0.68	0.63	3.51
600	Mean	12.53	8.81	11.51	11.91	4.50	4.19	6.67
	St. Dev.	1.13	1.07	1.20	1.38	0.68	0.63	3.34
900	Mean	12.15	8.74	11.36	11.75	4.49	4.18	6.61
	St. Dev.	1.36	1.05	1.01	1.31	0.68	0.63	3.25
1200	Mean	11.93	8.71	11.14	11.46	4.49	4.18	6.54
	St. Dev.	1.40	1.05	1.29	1.52	0.68	0.63	3.18
1800	Mean	11.40	8.66	10.99	11.15	4.47	4.16	6.45
	St. Dev.	1.35	1.01	1.17	1.40	0.68	0.63	3.04
2400	Mean	11.21	8.44	10.93	10.72	4.44	4.13	6.33
	St. Dev.	1.24	1.10	1.14	1.39	0.68	0.64	2.91
3000	Mean	10.43	8.32	10.21	10.19	4.40	4.09	6.15
	St. Dev.	1.45	0.98	1.33	1.42	0.68	0.61	2.72
3600	Mean	10.21	8.07	10.04	9.88	4.36	4.05	6.03
	St. Dev.	1.24	0.95	1.42	1.41	0.68	0.61	2.61
4200	Mean	9.74	7.83	9.54	9.40	4.32	4.03	5.87
	St. Dev.	1.28	1.01	1.54	1.27	0.68	0.60	2.16
4800	Mean	9.22	7.57	9.05	8.98	4.27	3.98	5.70
	St. Dev.	1.09	0.92	1.32	1.30	0.67	0.59	2.27
5400	Mean	9.07	7.32	9.00	8.69	4.18	3.88	5.56
	St. Dev.	1.02	0.82	1.63	1.17	0.66	0.57	2.21
6000	Mean	8.47	7.18	8.43	8.15	4.07	3.78	5.34
	St. Dev.	0.98	0.91	1.56	1.16	0.67	0.54	2.04
6600	Mean	8.45	6.82	7.83	7.95	4.05	3.76	5.25
	St. Dev.	1.28	0.92	1.34	1.17	0.65	0.56	1.96
7200	Mean	7.66	6.33	7.30	7.26	3.88	3.63	4.92
	St. Dev.	1.03	0.80	1.19	0.96	0.63	0.54	1.71
7800	Mean	7.60	6.20	6.79	7.18	3.82	3.58	4.84
	St. Dev.	1.03	0.89	0.94	0.91	0.60	0.49	1.68
8400	Mean	7.17	5.82	6.58	6.77	3.56	3.22	4.54
	St. Dev.	1.45	1.14	0.81	1.10	0.60	0.48	1.67

Table C.18: Acceleration Noise of Vehicle Groups for Different Flow Levels

Road III (14 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

	Acceleration Noise						
Flow (vph)	Car/Van/ Jeep (m/sec^2)	Tempo/ Auto Rickshaw (m/sec^2)	Bus/ LCV (m/sec^2)	Motorised Two Wheelers (m/sec^2)	Bicycle (m/sec^2)	Cycle Rickshaw (m/sec^2)	All Vehicles (m/sec^2)
600	0.162	0.023	0.104	0.042	0.004	0.008	0.023
900	0.207	0.036	0.123	0.066	0.011	0.014	0.035
1200	0.241	0.049	0.147	0.096	0.016	0.019	0.047
1800	0.340	0.071	0.220	0.147	0.035	0.045	0.077
2400	0.408	0.116	0.328	0.183	0.063	0.072	0.113
3000	0.491	0.138	0.378	0.219	0.091	0.106	0.145
3600	0.492	0.178	0.462	0.233	0.121	0.135	0.173
4200	0.563	0.203	0.517	0.245	0.140	0.153	0.196
4800	0.567	0.232	0.632	0.282	0.172	0.184	0.288
5400	0.632	0.261	0.640	0.296	0.212	0.223	0.263
6000	0.624	0.273	0.697	0.314	0.249	0.263	0.293
6600	0.632	0.302	0.835	0.326	0.265	0.275	0.312
7200	0.668	0.336	0.858	0.352	0.313	0.312	0.352
7800	0.705	0.345	0.832	0.351	0.333	0.338	0.367
8400	0.714	0.374	0.955	0.381	0.410	0.415	0.429

Table C.19: Traffic Concentration for Different Flow Levels

Road III (14 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

Flow (vph)	Concentration							
	No. of Vehicle per km		Road Occupancy (percent of road area)			Influence Area (percent of road area)		
	Mean	Max.	Mean	Max.	S.D.	Mean	Max.	S.D.
600	31	50	0.43	0.95	0.20	2.38	4.75	0.84
900	47	70	0.71	1.69	0.26	3.69	6.59	1.03
1200	64	98	0.96	1.99	0.30	5.03	8.74	1.31
1800	96	136	1.45	2.39	0.34	7.48	11.97	1.52
2400	131	172	1.86	2.66	0.46	9.82	13.82	1.81
3000	163	210	2.49	3.56	0.42	12.28	16.65	1.63
3600	201	226	3.06	3.76	0.50	14.88	17.26	1.74
4200	240	276	3.50	4.52	0.49	17.03	20.82	1.91
4800	289	342	4.42	5.31	0.48	20.63	23.67	1.90
5400	326	364	4.95	6.08	0.68	22.64	26.79	2.57
6000	374	412	5.46	6.25	0.50	24.64	27.03	1.69
6600	417	466	6.49	6.96	0.26	28.18	30.24	1.54
7200	498	504	7.49	7.95	0.27	30.54	32.43	1.40
7800	536	556	8.14	8.74	0.45	33.39	34.87	1.21

Table C.20: No. of Overtakings for Different Combinations of Vehicle Groups for Different Flow Levels

Road III (14 m Wide Road)
Traffic Composition of Level - I
Unrestricted Road Usage for Non-Motorised Vehicles

	No. of Overtakings								
Flow (vph)	Wide MV ov. Wide MV	Wide MV ov. Narrow MV	Narrow MV ov. Wide MV	Narrow MV ov. Narrow MV	Wide MV ov. Wide NMV	Wide MV ov. Narrow NMV	Narrow MV ov. Wide NMV	Narrow MV ov. Narrow NMV	Total
600	71	3	68	9	590	1687	530	1413	5632
900	95	7	118	14	861	2512	767	2101	8325
1200	109	12	134	17	1157	3242	996	2791	10979
1800	165	14	215	27	1722	4825	1421	4091	16233
2400	226	25	273	40	2248	6296	1797	5355	21326
3000	208	29	288	48	2830	7740	2167	6442	25928
3600	239	37	339	56	3294	9201	2639	7615	31920
4200	269	47	321	58	3727	10305	3018	8560	35004
4800	313	74	377	85	4146	11586	3352	9688	39449
5400	331	74	408	92	4731	13033	3881	10899	4463
6000	367	87	468	120	5258	14549	4264	11935	48044
6600	437	81	569	99	5518	15194	4594	12793	52827
7200	529	147	694	167	5990	16525	4929	13597	56783
7800	651	159	834	201	6277	17310	5293	14851	60835
8400	921	174	1010	173	6832	19373	5986	17221	68328